GFDL

GEOPHYSICAL FLUID DYNAMICS LABORATORY

ACTIVITIES – FY88
PLANS – FY89

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
Environmental Research Laboratories

75 Years Stimulating America's Progress ★ 1913-1988

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September 1988

Geophysical Fluid Dynamics Laboratory
Princeton, New Jersey

UNITED STATES
DEPARTMENT OF COMMERCE

C. WILLIAM VERITY
SECRETARY OF COMMERCE

NATIONAL OCEANIC AND
ATMOSPHERIC ADMINISTRATION

William E. Evans
Under Secretary and Administrator

Environmental Research
Laboratories

Vernon E. Derr
Director

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PREFACE

This document is intended to serve as a summary of the work accomplished at the Geophysical Fluid Dynamics Laboratory (GFDL) and to present a glimpse of the near future direction of its research plans.

It has been prepared within GFDL and its distribution is primarily limited to GFDL members, to interested offices of the National Oceanic and Atmospheric Administration, and to other relevant government agencies and national organizations.

The organization of the document encompasses an overview, project activities and plans for the current and next fiscal years, and appendices. The overview covers highlights of the five major research areas that correspond to NOAA's mission in oceanography and meteorology: Weather Service; Climate; Atmospheric Quality; Marine Quality; Ocean Service. These are five of the NOAA categories (bins) for research activities. The body of the text describes goals, specific recent achievements and future plans for the following major research categories: Climate Dynamics; Middle Atmosphere Dynamics and Chemistry; Experimental Prediction; Oceanic Circulation; Planetary Circulations; Observational Studies; Hurricane Dynamics; Mesoscale Dynamics; and Convection and Turbulence. These categories, which correspond to the internal organization of research groups, are different from the NOAA bins and are far from being mutually exclusive. Interaction occurs among the various groups and is strongly encouraged.

The appendices contain the following: a list of GFDL staff members and affiliates during Fiscal Year 1988; a bibliography of relatively recent research papers published by staff members and affiliates during their tenure with GFDL (these are referred to in the main body according to the appropriate reference number or letter); a description of the Laboratory's computational support and its plans for FY89; a listing of seminars presented at GFDL during Fiscal Year 1988; a list of seminars and talks presented during Fiscal Year 1988 by GFDL staff members and affiliates at other locations.

Although the specific names of individuals are not generally given in the overview, an entire listing of project participants can be found in Appendix A. Research staff personnel can normally be identified by consulting the cited Appendix B references or the names listed in the body of the text.

The 1988 Annual Report was co-edited by Frank B. Lipps and Betty M. Williams.

September 1988

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AN OVERVIEW

SCOPE OF THE LABORATORY'S WORK

The Geophysical Fluid Dynamics Laboratory is engaged in comprehensive long lead-time research fundamental to NOAA's mission.

The goal is to expand the scientific understanding of those physical processes which govern the behavior of the atmosphere and the oceans as complex fluid systems. These fluids can then be modeled mathematically and their phenomenology studied by computer simulation methods. In particular, research is conducted toward understanding:

- the predictability of weather, large and small scale;
- the particular nature of the Earth's atmospheric general circulation within the context of the family of planetary atmospheric types;
- the structure, variability, predictability, stability and sensitivity of climate, global and regional;
- the structure, variability and dynamics of the ocean over its many space and time scales;
- the interaction of the atmosphere and oceans with each other, and how they influence and are influenced by various trace constituents.

The scientific work of the Laboratory encompasses a variety of disciplines: meteorology; oceanography; hydrology; classical physics; fluid dynamics; chemistry; applied mathematics; high-speed digital computation; and experiment design and analysis. Research is facilitated by the Atmospheric and Oceanic Sciences Program which is conducted collaboratively with Princeton University. Under this program, regular Princeton faculty, research scientists, and graduate students participate in theoretical studies both analytical and numerical, and in observational experiments, both in the laboratory and in the field. The program, in part, is supported by NOAA funds. Research scientists visiting GFDL may also be involved through institutional or international agreements, or through temporary Civil Service appointments.

The following sections of the Annual Report describe the GFDL contribution to five major research areas that correspond to NOAA's mission in oceanography and meteorology.

HIGHLIGHTS OF FY88

and

IMMEDIATE OBJECTIVES

In this section, some research highlights are listed that may be of interest to those persons less concerned with the details of GFDL research. Selected are items that may be of special significance or interest to a wider audience.

Items in this section are placed in the NOAA emphasis categories of Weather Service, Climate, Atmospheric Quality, Marine Quality, and Ocean Service. These categories are organized rather differently than the GFDL research project areas presented in the main body of the report. References to more detailed discussions are given in parentheses.

I. WEATHER SERVICE

GOALS

During the past two decades synoptic-scale weather forecasts have improved considerably because of the development of numerical models that include more of the physical processes of the atmosphere, have high spatial resolution, and parameterize turbulent processes more accurately. Successful forecasts for period up to five days are now routine, and the limits of atmospheric predictability have been extended to several weeks. However, quantitative precipitation forecasts remain elusive. For smaller spatial scales, there has been considerable progress in determining the mechanisms that generate severe storms, in explaining how mesoscale phenomena interact with the large-scale flow, and in simulating the genesis, growth, and decay of hurricanes.

These successes in the extension of atmospheric predictability encourages asking more challenging questions. Can the weather be predicted on time-scales of months? Are mesoscale weather systems and regional scale precipitation patterns predictable, and if so, is the accuracy dependent on the prediction of the ambient synoptic flow? Research to develop mathematical models for improved weather prediction will also contribute to the understanding of such fundamental meteorological phenomena as fronts, hurricanes, severe storms, and tropospheric blocking.

ACCOMPLISHMENTS OVER THE PAST YEAR (FY88)

* Using an air-sea coupled model of reasonable space resolution, a seasonal forecast experiment was attempted for the first time. The initial conditions are prepared using data assimilation systems for both the ocean and the atmosphere. A case study indicates that some predictive skill is evident in the forecasts of sea surface temperature and the surface wind pattern at 3 or 4 months ahead. However, systematic biases in the sea surface temperature forecast are a serious problem (3.4.3).

* The study of ENSO with an atmospheric GCM indicates that the observed SO (Southern Oscillation) index is well represented if the sea surface temperature is specified correctly, and that westerly bursts of appreciable intensity occur in the model's western Equatorial Pacific in conjunction with the SO index swing from positive to negative. This transition of the SO index appears to take place in association with the emergence of a distinct pattern of sea surface temperature over the Pacific and the Indian Ocean (3.2.3).

* Analyses of numerical simulation for tropical cyclones data indicate that the cyclonic vorticity increases in a much deeper layer in a developing system, mainly due to vorticity stretching and relative advection, than in a non-developing system. Results from a sensitivity study suggest that the vortex-evaporation feedback mechanism is not always required for an incipient disturbance to develop into a system with tropical storm intensity, but it may make a storm more intense and compact. Simulation experiments were conducted to investigate tropical storm genesis under the influence of topographically affected flow as well as that in the environment of westerly vertical shear (7.1).

* A diabatic initialization scheme for tropical cyclones has been tested with a nested mesh model using a real data set. Also, a new open lateral boundary condition was formulated in a continuing effort to prepare an advanced operational model for the National Meteorological Center. The new scheme is original in that gradients of a field of a global model are employed for constraining the boundary of a regional model (7.2).

* A three-dimensional numerical study of the life cycle of unstable baroclinic waves has reproduced a realistic occlusion pattern of warm and cold fronts. Saturation of the wave's amplitude was found to be achieved through a meridional mixing of the horizontal temperature gradient and an enhancement of the static stability. The relative importance of each of these was found to be dependent on the Richardson number of the basic state (8.1.1).

* Two-dimensional simulations with/without the inclusion of a simplified ice bulk cloud physics have been carried out for an African squall line. In agreement with observations, the model with the inclusion of ice gave a mean propagation speed of 14 m s^{-1} and a 3 km deep layer with rear-to-front flow beneath the long trailing anvil. Both models gave a 4 K temperature drop behind the front and peak values of rainfall greater than 2 cm as observed. However, in disagreement with observed data, both models gave a 0.5 mb pressure rise behind the front instead of 2 mb as observed (9.3).

SOME PLANS FOR FUTURE RESEARCH

* Numerical models will be under continual development to improve forecasting of the large scale, the mesoscale, hurricanes, and squall lines, with emphasis on improved parameterizations of orography, cloud-radiation interaction and various subgrid-scale effects.

* Diagnostic analysis will be employed to improve understanding of essential weather processes relevant to prediction of atmospheric and oceanic phenomena with short, medium and long time scales.

* Collaboration will continue with the National Meteorological Center, both in the development of the Medium Range Forecast Model and the new MMM (Multiply-Nested Movable Mesh) model for operational hurricane forecasting. Hurricane Gloria will be used as a test case for the latter model.

II. CLIMATE

GOALS

The purpose of climate related research at GFDL is twofold; to describe, explain and simulate climate variability on time-scales from seasons to millenia; and to evaluate the climatic impact of human activities such as the release of CO_2 and other gases in the atmosphere. The phenomena that are studied include: large-scale wave disturbances, and their role in the general circulation of the atmosphere; the seasonal cycle, which must be defined before departures from the seasonal cycle (interannual variability) can be understood; interannual variability associated with phenomena such as the Southern Oscillation-El Niño; very long-term variability associated with the ice ages; and the meteorologies of various planets, the study of which enhances our perspective on terrestrial meteorology and climate. To achieve these goals, both observational and theoretical studies are necessary. Available observations are analyzed to determine the physical processes by which the circulations of the oceans and atmospheres are maintained. Mathematical models are constructed to study and simulate the ocean, the atmosphere, the coupled ocean, atmosphere and cryosphere system, and various planetary atmospheres.

ACCOMPLISHMENTS OVER THE PAST YEAR (FY88)

* The response of a global ocean-atmosphere GCM to a gradual increase of atmospheric carbon dioxide has a large interhemispheric asymmetry, similar to the results from an earlier model with idealized sector geography. After 200 years of integration, the surface temperature of the Antarctic circumpolar ocean hardly increases because of the upwelling and surface spreading of deep unmodified water which has not experienced CO_2 warming (1.2.1).

* Analysis of a long-term integration of a coupled ocean-atmosphere GCM shows interdecadal fluctuations of surface air temperature comparable with observations; greater variability in high latitudes is simulated (1.2.2).

* Numerical experiments have shown that land surface processes fundamentally influence the temporal variability of the lower atmosphere. By comparing the results from two long-term GCM integrations, it was demonstrated that the persistence of soil moisture anomalies substantially increases the persistence of near surface relative humidity on the seasonal and interannual time scales by altering the surface fluxes of latent and sensible heat (1.1).

* Numerical experiments conducted using GCMs with and without orography indicate that major mountain ranges such as the Tibetan Plateau and Rocky Mountains are responsible for extending the arid and semiarid regions of the subtropics poleward, thereby maintaining the Gobi and other deserts and steppes of the midlatitude Northern Hemisphere (1.4).

* The sensitivity of the atmospheric circulation to SST anomalies situated in the extratropics has been demonstrated in a 35-year GCM experiment which incorporates observed month-to-month SST changes in the World Oceans. The model results indicate that these SST anomalies are not only associated with perturbations in the seasonally averaged flow pattern, but also with the displacement of the maritime storm tracks (6.2.3).

* It is shown that a GCM can generate a realistic distribution of high cloud which is consistent with the satellite observations of high cloud frequency and outgoing terrestrial radiation (1.5).

* A SKYHI model simulation of the stratosphere Semiannual Oscillation (SAO) has achieved a very close resemblance to observations. Somewhat surprisingly the mechanism producing the westerly mean flow acceleration results from relatively smaller scale, vertically propagating gravity waves. Traditionally, this forcing was thought to result from equatorial Kelvin waves. Some recent observations appear to be consistent with the gravity wave mechanism (2.2.5).

* By comparing the predictions of a linear stationary wave model with the stationary eddies produced by idealized GCMs designed for the purpose, more convincing tests of the validity of linear stationary wave theory have become

possible. The stationary eddies forced by midlatitude topography of varying heights have been studied in isolation, as have the responses to zonal asymmetries in tropical sea surface temperature (1.7.2, 1.7.3).

* The essential dynamical mechanism responsible for the asymmetric life cycle of baroclinic eddies in the atmosphere -- baroclinic growth followed by barotropic decay -- has been isolated in an idealized, weakly unstable, two-layer model (1.8.2).

* The atmospheric energetics in the frequency domain of observed and GCM-simulated data indicate that the conversion from available potential energy to kinetic energy is a major source of the kinetic energy of tropical and extratropical low frequency oscillations (1.9).

* The dynamical invariants of global circulations were isolated in parameter studies with a GCM. The dynamical range of circulations was then found to be limited to the mix of a few elementary forms (5.1.1).

SOME PLANS FOR FUTURE RESEARCH

* The study of the effect on climate variability of interactions between the land surface and the atmosphere will be continued, using output from a general circulation model.

* The study of the response of the model climate to a gradual increase of atmospheric CO_2 will be continued, using the global coupled model which includes seasonal variation of solar insolation.

* The study of the role of cloud feedback in the CO_2 induced changes of tropical disturbances will be continued, using a high resolution version of the interactive cloud model.

* The influence of the orbital parameters of the earth upon climate will be investigated by using an atmospheric GCM coupled with a simple mixed layer ocean model.

* The continuing study of the idealized GCM's response to isolated topography and isolated SST anomalies in the tropics will be complemented by a study of its response to isolated midlatitude SST anomalies.

* Based upon the results from the high spectral resolution computations of solar and terrestrial radiation, an improved radiation algorithm has been developed and will be incorporated into GCM's.

* The computation of solar radiation at high spectral resolution will continue in order to provide a benchmark for the intercomparison of radiative transfer algorithms.

* The high resolution SKYHI stratospheric model will be integrated further and analyzed in greater depth.

III. ATMOSPHERIC QUALITY

GOALS

The main goal of atmospheric quality research at GFDL is to understand the formation, transport, and chemistry of atmospheric trace constituents on regional and global scales. Such understanding requires judicious combinations of theoretical models and specialized observations. The understanding gained will be applied toward evaluating the sensitivity of the atmospheric chemical system to human activities.

ACCOMPLISHMENTS OVER THE PAST YEAR (FY88)

* The GFDL 3-D global tracer model has been used to study the behavior of reactive nitrogen (NO_y) emissions. The simulated wet deposition in Europe and at more remote sites in the Northern Hemisphere agree well with available observations. This study indicates that Asia provides the major source of NO_y over the North Pacific and that European emissions dominate Arctic haze, particularly in the lower troposphere. Emissions from fossil fuel combustion appear to constitute less than 10% of the NO_y observed at remote locations in the Southern Hemisphere (2.1.1).

* A study of the effect of cyclones on ozone transport in high latitudes of the southern hemisphere suggests that cyclonic activity may enhance and sharpen gradients of any tracer, such as ozone, that decreases toward the pole. An investigation of a typical, strong austral cyclone that developed over the Palmer Peninsula of Antarctica on 5 September 1987 indicates a strong correlation of storm development with low column-integrated ozone concentrations observed in the region (8.3.2).

* The downward flux of tritium due to deep convection has been simulated using a two-dimensional convection model. It is verified that a key factor in determining the downward flux of tritium in the atmosphere is the speed at which tritium is able to escape from falling precipitation. Present calculations indicate that deposition into the ocean by vapor diffusion can continue long after rain and the concurrent deposition by rainout has stopped. As shown in Fig. 9.1, this effect can give rise to larger values of total deposition by vapor diffusion than by rainout (9.4).

SOME PLANS FOR FUTURE RESEARCH

* Work will continue on the regional/global transport, chemistry, and removal of chemically and climatically important trace gases. A self-determined ozone chemistry will be inserted into the SKYHI GCM.

* Moist chemical removal parameterization processes will be developed for use in convective and large scale models.

IV. MARINE QUALITY

GOALS

Research at GFDL related to the quality of the marine environment has as its objectives the simulation of oceanic conditions in coastal zones and estuaries, the modeling of the dispersion of geochemical tracers (tritium, radon ...) in the world oceans, and the modeling of the oceanic carbon cycle and trace metal geochemistry. For regional coastal studies two- and three-dimensional models of estuaries such as the Hudson-Raritan and Delaware Estuaries are being developed. The response of coastal zones to transient atmospheric storms, and the nature of upwelling processes which are of great importance to fisheries, are being studied by means of a variety of models. Basin and global ocean circulation models are being developed for the study of the carbon cycle and trace metal cycling.

ACCOMPLISHMENTS OVER THE PAST YEAR (FY88)

* Carbon cycle models have advanced from studies in an idealized sector ocean model to a full, World Ocean configuration (4.3.1).

* Significant progress has been made in developing the code for a trace metal scavenging routine that will be incorporated into the 3-D primitive equation ocean circulation and particle cycling model (4.3.2).

* Work is continuing on the South Atlantic Ventilation Experiment which is continuation of the Transient Tracers in the Ocean program and the ARKTIS which is a program to collect oceanographic data from the Arctic Ocean (4.3.4).

SOME PLANS FOR FUTURE RESEARCH

* The effort will continue to incorporate biological effects in a coupled carbon cycle/ocean GCM.

* A wide range of analyses of ocean tracer data relative to ocean dynamical structure will continue.

V. OCEAN SERVICE

GOALS

A variety of models that can be used for the prediction of oceanic conditions are being developed at GFDL. The simpler models are capable of predicting relatively few parameters. For example, one-dimensional models of the turbulent surface layer of the ocean predict the sea surface temperature and heat content of the upper ocean. More complex three-dimensional models are being developed to study many phenomena: the time dependent development of Gulf Stream meanders and rings; generation of the Somali Current after onset of the southwest monsoons; response of coastal zones to atmospheric storms; and development of sea surface temperature anomalies such as those observed in the tropical Pacific Ocean during El Niño-Southern Oscillation phenomena.

ACCOMPLISHMENTS OVER THE PAST YEAR (FY88)

* The World Ocean circulation model used for climate studies has performed a rather realistic simulation of both natural and bomb produced Carbon-14. The model predicts that on time scales longer than a decade the major downward pathway into the ocean is located in the Southern Hemisphere just north of the Antarctic Circumpolar Current (4.4).

* Coupled General Circulation Models of the ocean and atmosphere have simulated interactions between these two media over a 28-year period. Although the forcing, the incoming solar radiation, is steady, the coupled system has a broad spectrum of variability that includes a realistic El Nino/ Southern Oscillation (ENSO) cycle (4.1).

* Realistic El Nino-Southern Oscillation (ENSO) phenomena have been simulated in two coupled ocean-atmosphere GCM experiments, one with a fine-mesh ocean and the other with a crude-resolution ocean. Comparison between the output for this pair of integrations yields fresh insights into the multiple dynamical processes at work during ENSO cycles (6.2.4).

* A study of oceanic adjustment in the presence of mean currents reveals that critical layer absorption can prevent the large-scale waves from reaching certain regions. Local Ekman suction rather than a Sverdrup balance dictates vertical thermocline movements in such regions (4.2.1).

* Numerical studies with the ocean GCM have revealed a serious deficiency in the simulation of the Equatorial Undercurrent and the maintenance of the thermocline. These deficiencies have been attributed to the method of handling the turbulent length-scale in the closure scheme of Mellor and Yamada (517). This investigation has subsequently led to a modification of the theory for the turbulent length-scale (3.1.7).

SOME PLANS FOR FUTURE RESEARCH

* Work will continue on the development of coupled ocean-atmosphere general circulation models. The capability of such models to simulate the interannual variability of the ocean-atmosphere system will be assessed.

* Detailed analysis of the behavior of ocean models will be underway with special emphasis on the new higher resolution models.

* Work will continue on ocean model developments with emphasis on ice dynamics, turbulent closure, and isopycnal coordinates.

* Detailed comparisons of coastal model behavior against observations will be carried out.

PROJECT ACTIVITIES FY88

PROJECT PLANS FY89

1. CLIMATE DYNAMICS

GOALS

* To construct mathematical models of the atmosphere and of the joint ocean-atmosphere system which simulate the global large-scale features of climate

* To study the dynamical interaction between large-scale wave disturbances and the general circulation of the atmosphere.

* To identify and elucidate the physical and dynamical mechanisms which maintain climate and cause its variation.

* To evaluate the impact of human activities on climate.

1.1 LAND SURFACE-ATMOSPHERE INTERACTION

T. Delworth
S. Manabe

ACTIVITIES FY88

Investigations into the role of land surface processes in climate variability (ja) have been continued during the past year. Efforts were focused on identifying the influence of soil moisture on the temporal variability of near surface atmospheric variables in a GCM.

For this purpose, comparisons were made between the results of two long term GCM integrations with prescribed sea surface temperatures. In the first experiment (50-year integration), soil moisture was computed interactively. In the second experiment (25-year integration), the seasonal cycle of soil moisture was prescribed at each grid point based upon the results of the first experiment. As a result, differences in atmospheric variability between the two experiments were due to the presence of interactions between the soil layer and the atmosphere in the first experiment.

Anomalies of soil moisture in the first experiment may have very long time scales (several months to a year). The persistent nature of these anomalies causes persistent anomalous fluxes of latent and sensible heat, and therefore persistent anomalous near surface atmospheric humidity and temperature. This can be seen with the use of an index of monthly men relative humidity near the surface, computed as the monthly mean mixing ratio divided by the saturation mixing ratio corresponding to the monthly mean temperature. At each grid point, using data from the months of April through September, time series of this index were correlated with the same time series, but lagged one month. The large the autocorrelation value thus computed, the more persistent the time series is. For the experiment in which soil moisture was prescribed, there is virtually no persistence of relative humidity, as inferred from autocorrelation values close to zero (not shown). However, for the experiment in which soil moisture was computed interactively, the autocorrelation values shown in Figure 1.1 reveal a substantial month to month persistence of near surface relative humidity over continental regions. This persistence results from interactions between the soil layer and the atmosphere, and is strongest where values of potential evaporation are large.

PLANS FY89

The analysis of the influence of interactive soil moisture on model atmospheric temporal variability will be continued. In particular, the seasonal and geographical variations of the influence of interactive soil moisture on model persistence will be explored. The mechanism by which soil moisture influences atmospheric persistence will be examined further.

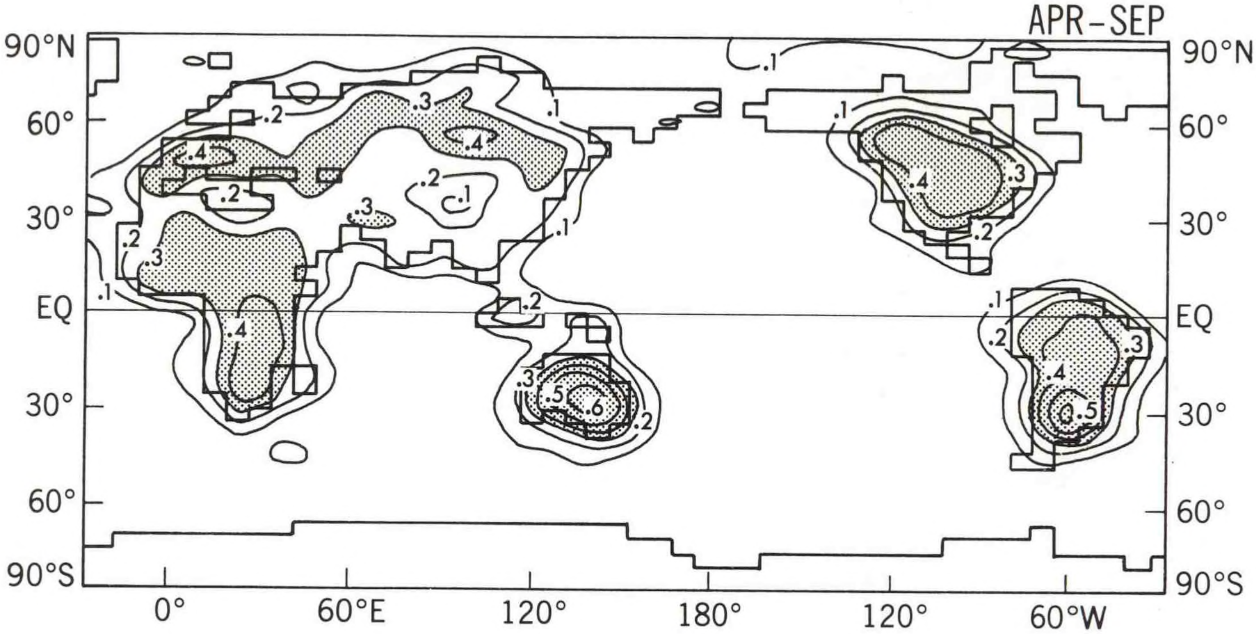

Fig. 1.1 Autocorrelation values of the index of monthly mean relative humidity near the surface. At each grid point, values of this index were correlated with values of the same index one month later. Positive values denote a persistence of anomalies. The correlations were computed using data only from the months of April through September.

1.2 OCEAN CIRCULATION AND CLIMATE

K. Bryan M. Spelman
K. Dixon R. J. Stouffer
S. Manabe

1.2.1 Interhemispheric Asymmetry in CO_2 Warming

ACTIVITIES FY88

The study of the transient response of climate to increasing atmospheric CO_2 using a coupled ocean-atmosphere model was continued during the past year. Previous studies have used a coupled model with a limited sector computational domain, idealized geography, and annually averaged solar insolation (484, 567, 678, 699, 700, 870). These studies have been extended by using a global model with realistic geography. The transient response of climate was studied for two different cases, one with an abrupt doubling of atmospheric CO_2 and the other with a gradual buildup of CO_2 content. Recently, a time integration of 200 years was completed for the gradually-increasing CO_2 case, along with a parallel control integration without the CO_2 increase. Beginning from the year 1950, the CO_2 content in the first integration was increased at the rate of 0.8 percent per year. Given this rate of increase, a doubling of CO_2 occurs after 87 years, i.e., around the year 2037. This scenario is within the range of projected increases of the combined effects of all greenhouse gases.

The change of surface temperatures produced by the gradual CO_2 buildup is presented in Fig. 1.2. The lower part of this figure is the zonally averaged sea surface temperature change at each latitude for the entire 200 years of model integration. The upper part of the figure is the corresponding change of surface air temperature. In high latitudes of the Southern Hemisphere, the sea surface temperature fails to increase and the surface air temperature response has only a slight increase even after 200 years of integration, during which the CO_2 concentration increased by a factor of more than four. In this region, upwelling of unmodified waters from the deep ocean prevents a significant warming of the surface water and delays the response to the CO_2 increase. Because the CO_2 warming is much larger over the remainder of the globe, a large interhemispheric asymmetry appears in the surface temperature change. This feature is in qualitative agreement with results from the preceding study (870) using an idealized coupled model.

PLANS FY89

The study of the response of the model climate to a gradual increase of atmospheric carbon dioxide will be continued, using an upgraded version of the global coupled model which includes seasonal variations of solar insolation.

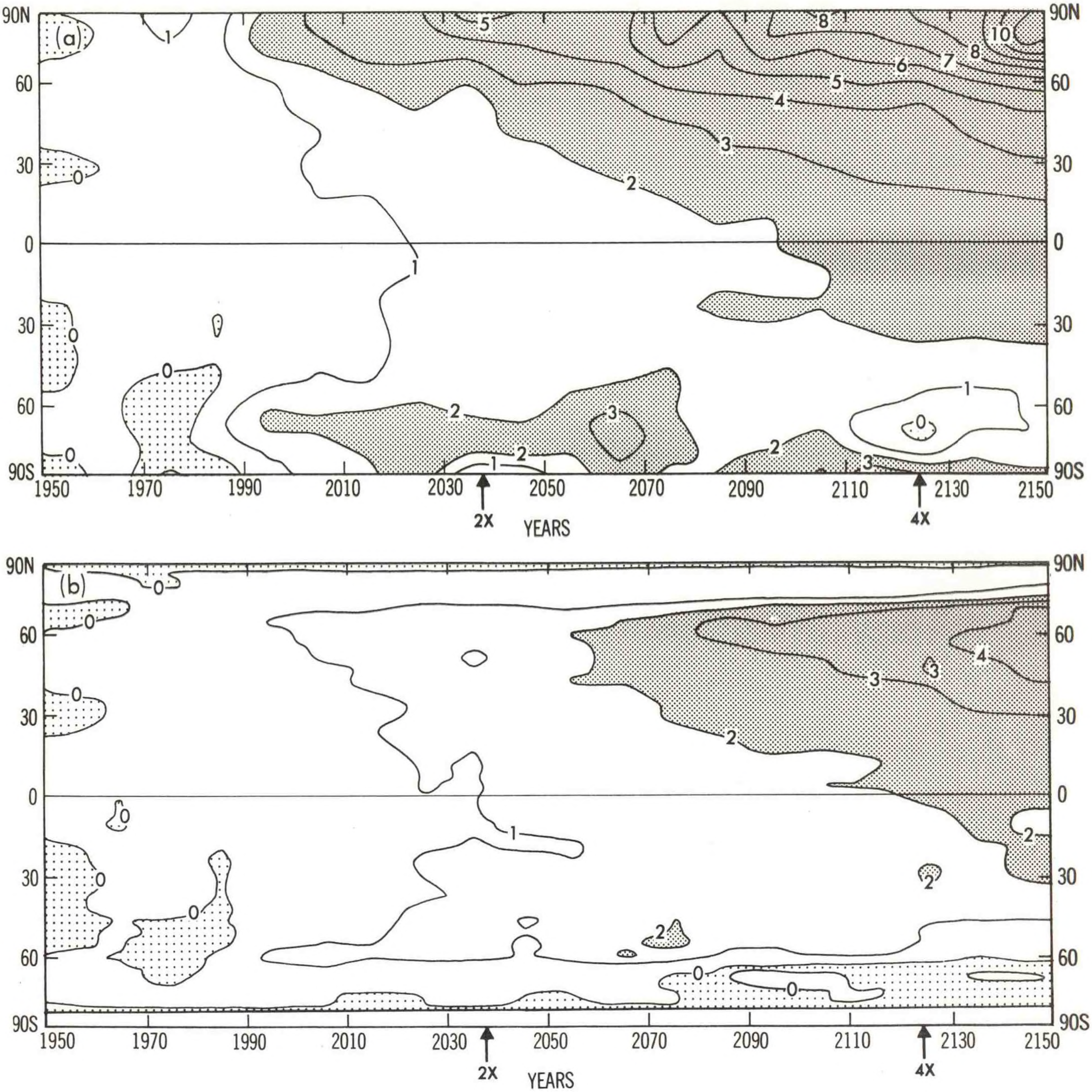

Fig. 1.2 Changes of zonally averaged temperature in degrees Celsius as a function of time and latitude for the gradual buildup of atmospheric carbon dioxide: (a) surface air temperature, (b) sea surface temperature, 2X (and 4X) denote the year when carbon dioxide content is double (and four times) the initial value. The changes represent the differences between the two integrations with and without the CO_2 buildup.

1.2.2 Variability of a Coupled Ocean-Atmosphere GCM

ACTIVITIES FY88

To study the influence of the oceans on the variability of climate, a low resolution coupled ocean-atmosphere model was time-integrated for over 100 model years. The model has a global computational domain, realistic geography and annually averaged insolation.

Figure 1.3 illustrates the temporal variation of surface air temperature averaged over several latitude belts in the Northern Hemisphere of the model. For reference, the corresponding distributions of surface air temperature in the actual atmosphere are also included. The thin lines in the figure represent annual mean data, while the thick lines represent 5-year running means. The model data were detrended at each grid point. This figure indicates that although the temporal fluctuation with a time scale of almost one century is contained in the observed distribution, it is not evident in the time series from the model. Obviously, the detrending mentioned above eliminates whatever long term trend the model might have. It is encouraging, however, that the model does simulate the magnitude of the interannual to interdecadal variability. One can also see that there is a high latitude amplification of the variability both in the computed and observed time series.

Figure 1.3 also indicates that, averaged over the Northern Hemisphere, the surface air temperature of the model has fluctuations of a few tenths of a degree centigrade on the decadal to interdecadal time scales. For the same time scales the temporal fluctuations are much smaller in a long term integration of an atmospheric GCM which used prescribed sea surface temperatures (i.e., without ocean-atmosphere interaction) (474,ja). These results indicate that the interaction between the ocean and atmosphere has a significant influence upon the long term fluctuations of hemispheric (or global) mean surface air temperature and should not be neglected in any attempt to identify present or future warming induced by greenhouse gases.

PLANS FY89

The analysis of this experiment will continue with the goal of identifying the mechanisms which contribute to the temporal variability of the coupled system.

1.3 CO_2 AND TROPICAL DISTURBANCES

A. J. Broccoli
S. Manabe

ACTIVITIES FY88

The global warming produced by climate models in response to increased atmospheric CO_2 has led some to speculate that tropical cyclone activity may increase as greenhouse gases warm the climate. Motivated by this speculation and the successful simulation of tropical cyclone-like disturbances in an earlier generation of GFDL climate models (92), a series of CO_2 sensitivity experiments was analyzed in an effort to detect changes in the simulated climatology of tropical disturbances.

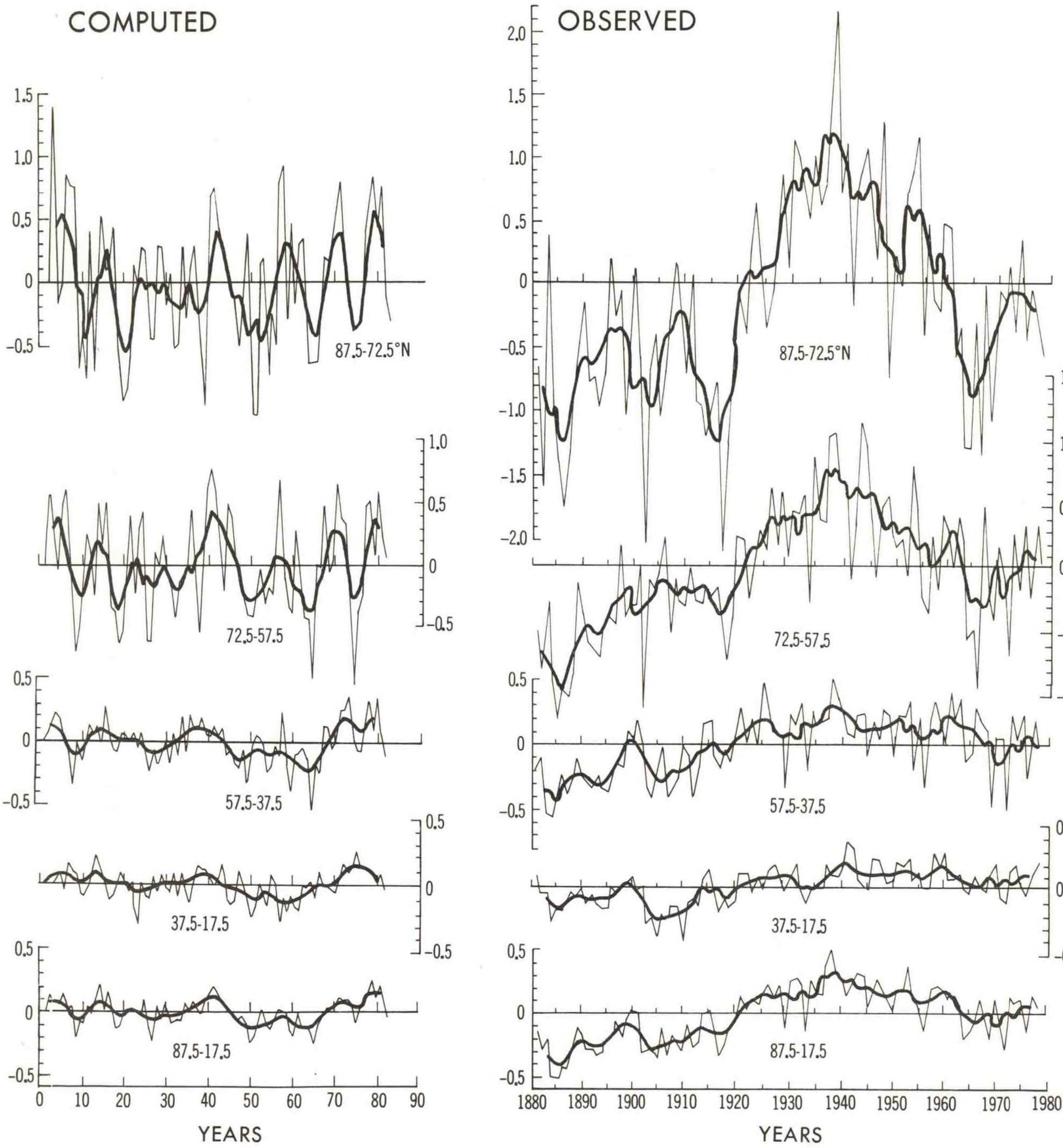

Fig. 1.3 Surface air temperature distributions averaged over several Northern Hemisphere latitude belts. The temperature scales are in degrees C. The thin lines represent annual mean data and the thick lines represent 5 year running means. The observed data are from Vinnikov et al. (Meteorologiya i Gidrologiya (1980)).

A system was developed to identify cyclonic vortices over the tropical oceans in three pairs of climate model integrations, each consisting of a control and doubled CO_2 case. Two pairs of integrations used prescribed cloudiness (varying only with latitude and height) with horizontal resolutions of R15 and R30; the other pair with R15 resolution used a scheme that predicts cloud cover, thereby incorporating the interaction between cloud and radiative transfer in the atmosphere. In each of the control integrations cyclonic vortices were simulated in the regions where tropical cyclones occur in the real atmosphere, with frequencies similar to observed. While neither resolution is sufficient to simulate in detail the intense pressure gradients and rainbands of tropical cyclones, the vortices resembled them in their warm core structure and were more realistic in appearance in the higher resolution integrations.

In response to increased CO_2 the global number of storm days (defined as the product of the number of individual vortices and their duration) undergoes a statistically significant increase in the experiments with prescribed cloudiness. This increase is induced by enhanced evaporation over the warmer oceans supplying more moisture to the tropical atmosphere. As this moisture converges in tropical disturbances it leads to a marked increase in precipitation, the generation of eddy available potential energy and in situ conversion to eddy kinetic energy. Since the warming of the tropical oceans is greater in the model with cloud feedback, the mechanism described above should operate even more strongly in this model, thereby producing a larger increase in storm days. Instead, a different result occurs; the global number of storm days fails to increase in the high CO_2 world. The results from the model with cloud feedback are currently being studied in an effort to identify how cloud-radiation interaction alters or counteracts this mechanism of storm intensification.

PLANS FY89

A pair of integrations of the R30 version of the model with interactive cloudiness is underway to complete the set of experiments described above. Further analysis of these experiments along with those from the R15 model will be undertaken to elucidate the role of cloud feedback in the CO_2 induced changes in tropical disturbances.

1.4 CLIMATE AND OROGRAPHY

A. J. Broccoli
S. Manabe

ACTIVITIES FY88

An experiment was carried out to investigate the effects of orography on global climate, particularly the distribution of arid and semiarid regions, using the high resolution (R30) climate model. Two integrations were performed: one with realistic geography and orography (the control integration), and the other with realistic geography but flat continental surfaces (the NM integration). This experiment is similar to one performed some years ago with a gridpoint climate model (162, 206) in which topography was found to substantially alter the global climate. The recent incorporation of a gravity wave drag parameterization in the high resolution model made this experiment worthwhile by improving the Northern Hemisphere climate simulation.

In an effort to compare the NM and control integrations, a climatic classification scheme developed by Köppen was assigned to every gridpoint based on the output from each integration. This scheme uses the temperature along with the annual precipitation and its seasonal distribution to determine a climatic classification designed to correspond to the prevailing vegetation. The Köppen climate maps for the control and NM integrations are presented in Fig. 1.4, along with a similar map for the observed climate distribution. An examination of these maps indicates that the distribution of dry climates (desert and steppe; Köppen's B category) from the control integration is quite similar to their observed distribution. While these dry climates are generally found in the subtropics, they extend into middle latitudes over central Asia, west central North America, and southern South America.

By contrast, the distribution of dry climates in the NM integration is much more zonal and confined to the subtropics. This is most notable over Asia where the steppe and desert extending from the Caspian Sea eastward to northern China in the control integration is replaced by more humid climates in the NM run, with the dry climates displaced southward across the Indian subcontinent. An examination of the circulation and precipitation distributions shows this to be the result of a jet stream and associated storm track that crosses the Eurasian continent, bringing increased warm season precipitation to central Asia. In the control experiment the Eurasian jet is much weaker and further north during the warm season, leaving central Asia in a dry subsidence region between this high latitude jet and the monsoon-induced south Asian low to the south.

PLANS FY89

Further analysis will be performed to explore the three-dimensional structure of the atmospheric circulation and climate over Asia in each integration and their relationship to the presence or absence of orography. In addition, changes in North American climate will be examined in more detail.

1.5 SIMULATION OF HIGH CLOUD

S. Manabe R. T. Wetherald
V. Ramaswamy

ACTIVITIES FY88

The results of several GCM experiments conducted at GFDL and other institutions have indicated that cloud feedback may play an important role in enhancing the sensitivity of climate to a forcing such as an increase of atmospheric carbon dioxide. In particular, a recent investigation (859) indicates that the change in the altitude of high cloud is an important part of this feedback process. Therefore, it is desirable to determine how well a current GCM is capable of simulating the seasonal and geographical distribution of high cloud cover. Data have now become available which present seasonal frequency distributions of high cloud or cirrus occurrences as obtained from the Stratospheric Aerosol and Gas Experiment (SAGE) satellite system. The current study is an attempt to evaluate the ability of the GCM to simulate high cloud cover by use of the SAGE data.

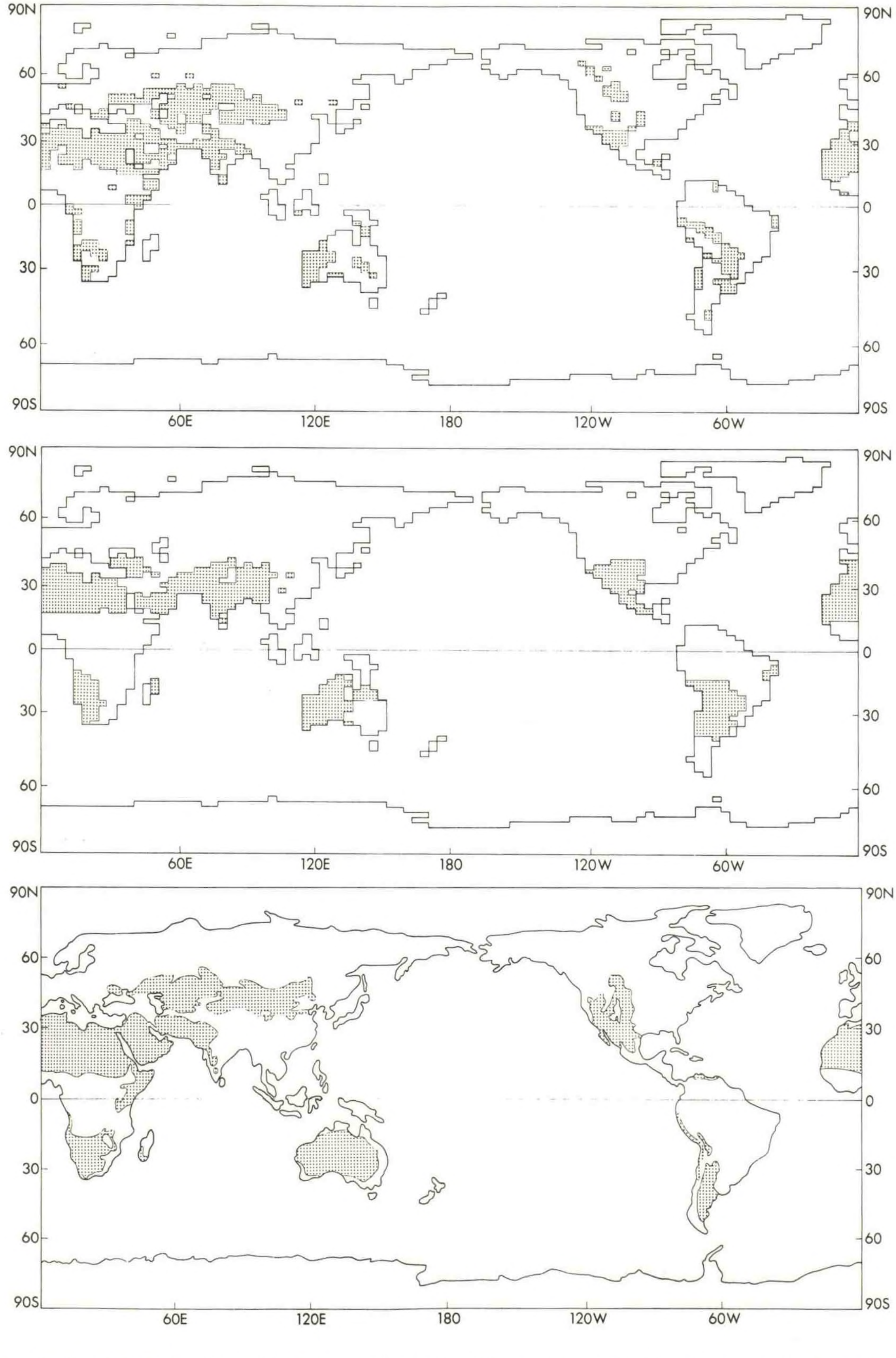

Fig. 1.4 Global distribution of semiarid and arid climates as determined by Köppen climatic classification: (top) control experiment, (center) NM experiment, (bottom) observed.

In Fig. 1.5 the simulated distribution of high cloud amount is compared with the observed frequency of high cloud from the SAGE satellite system. In general, the computed regions of maximum cloud amount (dark areas) in low latitudes (Fig. 1.5a) compare quite favorably with those of maximum high cloud frequency obtained from observations (Fig. 1.5b). A comparison was also made with the Earth Radiation Budget Experiment (ERBE) satellite measurements of longwave radiation at the top of the atmosphere. Upon comparison of these measurements with both the computed and observed distributions of high cloud cover, it was found that the regions of minimum emission corresponded quite closely with the dark areas of both cloud distributions and were, therefore, well correlated with the regions of high probability of cirrus occurrences. These results indicate that the model simulation of high cloud is well correlated not only with the observed regions of maximum high cloud frequency but also with the distribution of the outgoing terrestrial radiation.

It is worthwhile to note that the regions of minimum longwave emission include the tropical rainbelt which implies that these areas contain mostly optically thick high clouds. These facts, taken together, indicate that a direct relationship exists between the upward convective motions in the tropical rainbelt and the occurrence of optically thick anvil-type cirrus clouds which are produced at the tops of these convective clouds and spread to either side of the rainbelt.

In summary, the use of both observed high cloud frequency and outgoing terrestrial radiation data has indicated that a successful simulation of high cloud is obtained by the GCM particularly in the vicinity of the tropical rainbelt. These results provide more confidence in the ability to model the mechanism of cloud feedback in future climate sensitivity studies.

PLANS FY89

The analysis of this simulation study will be completed. In particular, emphasis will be placed upon the interaction among the distributions of cloud cover, outgoing terrestrial radiation and total precipitation.

1.6 ICE AGE MODELING

I. M. Held
P. J. Phillipps

ACTIVITIES FY88

A two-layer primitive equation model on the sphere, constructed in collaboration with M. Suarez (NASA Goddard), has been used to study the sensitivity to solar constant and orbital parameter variations. The model's sensitivity to changes in the solar constant, in the idealized case of annual mean forcing, "swamp" lower boundary conditions, and fixed albedos, is very similar to that of the Climate Dynamics R15 GCM. Its sensitivity in the presence of albedo feedback has also been determined and analyzed using a two-layer energy balance model. A novel result of this analysis is that changes in the vertical flux of energy by large scale motions must be taken into account to understand the model's behavior. It was found that this effect can be captured adequately in the energy balance model by relating the vertical flux of potential temperature to the horizontal flux, assuming that mixing occurs along an isentropic surface.

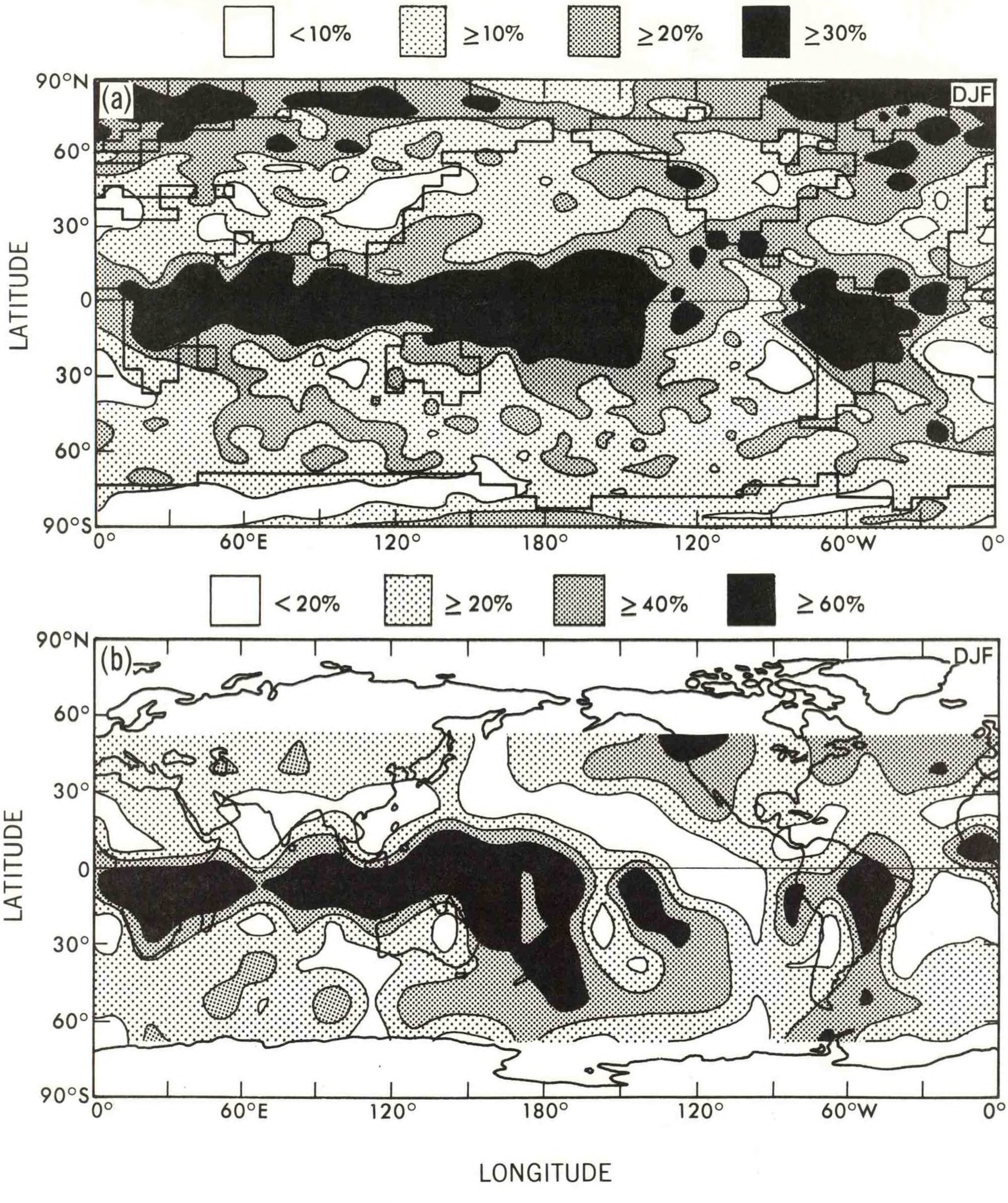

Fig. 1.5 December-January-February geographical distribution of (a) high cloud amount simulated by the GCM and (b) frequency of high cloud appearances determined by limb-sounding measurements from the SAGE satellite system (M.P. McCormick: J. Geophy. Res., 91). Results for the GCM are based upon a ten model year average whereas the SAGE measurements are taken over a three year period from 1979 to 1981. As indicated in the top and middle of the figure, the shading convention is chosen separately for the computed amount (a) and observed frequency (b) of high cloud.

When coupled to a mixed layer ocean and sea-ice model, and forced with seasonally varying radiation (using a realistic continental distribution), the model produces a climate that is satisfactory for a preliminary examination of the response to orbital parameters, except for one feature: the polar easterlies and the associated direct mean meridional circulation are much too strong. This direct circulation transports excessive amounts of water vapor equatorward, producing very dry polar regions. As a result, it is very difficult to generate Northern Hemisphere glaciation, even when the model climate is forced to be very cold. (A "glacier" in the model is simply a region in which the annual mean snowfall exceeds snowmelt, so that snow accumulates from year to year). Despite this difficulty, the response of the model to orbital parameter variations was examined and a large response in summertime temperature over the Northern Hemisphere continents (greater than 6K) and in the tropical precipitation pattern were obtained.

PLANS FY89

Work will continue with the two-layer model. However, because of this model's deficiencies, orbital parameter experiments are being planned with the Climate Dynamics Group R15 atmosphere-mixed layer ocean model to complement the more numerous calculations that can be performed with the two-layer model. Two experiments will be conducted with the R15 model; one with orbital parameters thought to be conducive to a warm climate (high obliquity and perihelion near summer solstice); and another with parameters conductive to a cold climate (low obliquity and perihelion near winter solstice).

1.7 STATIONARY WAVE MODELS AND IDEALIZED GCMs

K. H. Cook A. Gnanadesikan
I. M. Held M. Ting

ACTIVITIES FY88

1.7.1 A New Linear Stationary Wave Model

Work in which linear stationary wave theory is compared with the stationary eddies simulated in GCMs has continued. Previous studies (778,ik,jl) at GFDL have utilized a spherical primitive equation linear model which shares the GCM's vertical finite-differencing, but is finite-differenced in the meridional direction, in contrast to the spectral formulation of the GCM. In the past year, a new linear model has been constructed that is an exact linearization of the spectral GCM. This exact linearization is useful for detailed comparisons of linear theory and GCM eddies. For an R15, 9-level model, the new model is much more efficient than the old version, particularly if one needs to compute the response to a series of forcing functions, using the same basic state. For models with higher vertical resolution, the new version is far superior; for models with higher horizontal resolution, the old model is more efficient.

1.7.2 Stationary Waves in an Idealized GCM

A series of integrations of a GCM with idealized mountains is complete. An experiment with a flat, "swamp" lower boundary and a zonally symmetric climate is the control. This model is then modified by adding Gaussian mountains of various heights ($1/\sqrt{2}$, 1, 2, 3, and 4 km) centered at 45° latitude. The purpose of these experiments is to test the limits of linear theory in simulating orographically-forced stationary waves, and to examine the manner in which linear theory breaks down.

The response of the model's 300 mb geopotential, with the zonal mean removed, is shown in Fig. 1.6a for the 1 km mountain. A similar result is obtained for the smaller $1/\sqrt{2}$ km mountain when the response is scaled by the height of the mountain, indicating that the model's climatic response is close to being linear. Figure 1.6b shows the corresponding prediction of the linear stationary wave model. Although the linear response is somewhat larger, the overall agreement confirms that the 1 km case is close to the linear limit. This linear model is forced by the orography, as well as the asymmetric heating and transient eddy fluxes produced by the GCM. The orographic forcing is by far the dominant term, although the other terms do improve the agreement with the GCM slightly.

The cases with higher amplitude orography clearly show a "saturation" effect, in that the scaled amplitude of the forced stationary wave decreases with mountain height. The saturation is discernible in the 2 km mountain case, where the scaled amplitudes are smaller even though the structure of the wave is not dramatically different from the case with smaller mountains. Figures 1.6c and 1.6d show the scaled responses for the 3 and 4 km mountains. Not only is the saturation of the response evident in the decreased amplitudes, but the structure of the wavetrain has also changed markedly. The increased poleward signal results in a more pronounced response in high latitudes.

1.7.3 Stationary Eddies Generated by Latent Heating in the Tropics

An analysis of the importance of transients for the response of a GCM to El Niño sea surface temperature anomalies has been completed (jx). In this work, two distinct mechanisms by which the transients affect the extratropical wavetrain have been isolated. The first is the more familiar shift in the mid-Pacific storm track that accompanies the anomalous extratropical wavetrain. The stationary wave response to this shift was computed with a linear model, and was found to be responsible for a large part of the GCM's anomalous wave. Less familiar, but also of importance in the linear diagnosis of the GCM, is a shift in the location of the deceleration of the mean flow in the tropics resulting from Rossby waves propagating into the tropics from midlatitudes.

Our analysis suggests the following scenario for the creation of the extratropical wavetrain. First, the tropical heating modifies the equatorial zonal winds changing the propagation characteristics for Rossby waves entering the tropics. This modification results in a redistribution of eddy stresses which, when combined with the effects of the heating, force an extratropical wavetrain of modest amplitude. This wavetrain is then strongly reinforced by a shift in the Pacific storm track. Recent literature emphasizes the interaction of the tropically-forced wavetrain with the stationary extratropical waves, but this mechanism does not seem to play an important role in this model. A speculation is that this is because the forcing in this model is dominated by anomalous heating in the central Pacific. If the anomaly in the Indonesian region is dominant then this interaction may play a much more important role.

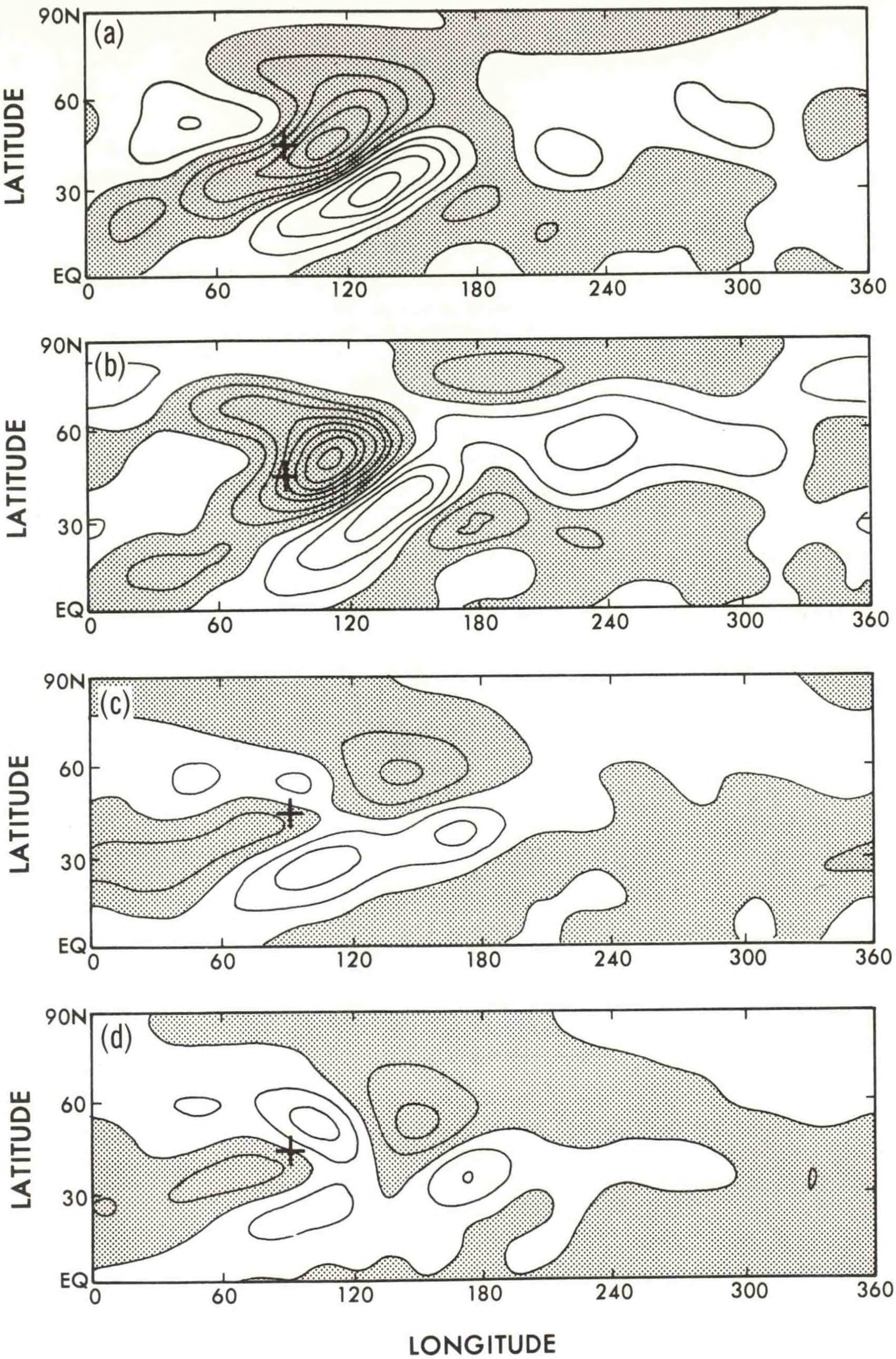

Fig. 1.6 Eddy streamfunction at 300 mb divided by the height of the mountain in km for a) idealized GCM 1 km mountain, b) linear model with orography and transient eddy forcing from the 1 km GCM climatology, c) GCM with 3 km mountain, and d) GCM with 4 km mountain. The top of the mountain is noted at 45°N and 90°E. Contour intervals are 10^6 m^2 s^{-1}.

To complement this work with a realistic GCM, the response to anomalous tropical sea surface temperature has been analyzed in a more idealized GCM. A model with zonally symmetric sea surface temperatures and perpetual January insolation was integrated as a control and then perturbed with an east-west dipole temperature anomaly along the equator. Two anomaly experiments have been performed: one in which the SST anomalies are +5K at the center of the dipoles, and another in which the anomalies at the center are +2.5K. The response in these experiments is remarkably linear. Figure 1.7a shows the GCM upper tropospheric eddy geopotential for the large +5K anomaly. The response for the smaller anomaly, when scaled by the size of the anomaly, is very similar. Figure 1.7b shows the linear model's simulation of this stationary wave, when forced by the GCM's diabatic heating and anomalous transient eddy fluxes. The transients in this calculation are found to play a relatively simple damping role to first approximation, in contrast to the positive feedback found in the realistic El Niño simulation.

1.7.4 Idealized GCM with Tropical Continent

A series of calculations with an idealized GCM are being performed to examine the effects of a tropical continent on atmospheric circulation as well as precipitation and evaporation patterns. The control run is once again a perpetual January, zonally symmetric SST with a zonally symmetric climate. A tropical continent is then introduced into the model, without changing the surface albedo or the surface roughness from its oceanic value. The resulting asymmetries in the circulation and hydrological cycle are being analyzed. An additional experiment with increased continental surface roughness has also been completed.

PLANS FY89

Analysis of the GCM experiments with idealized orography will continue. The responses of the heating and transient eddy flux fields to the presence of orography will be studied and their significance for the stationary flow examined. The response of the zonally averaged flow to the presence of the isolated orographic feature will be analyzed. The possibility of moving beyond linear theory by iteration or by some other method for finding approximate steady nonlinear solutions will be explored.

The transients in the idealized SST anomaly experiment will be analyzed further, in an attempt to understand the dramatically different role played by the transients in this experiment and in the realistic El Niño simulation. A similar study is being planned with a midlatitude SST anomaly, using the same perpetual January, zonally symmetric SST control run.

Analysis of the idealized tropical continent calculations will continue to evaluate the sensitivity of the general circulation to ground hydrology, surface roughness, and surface albedo.

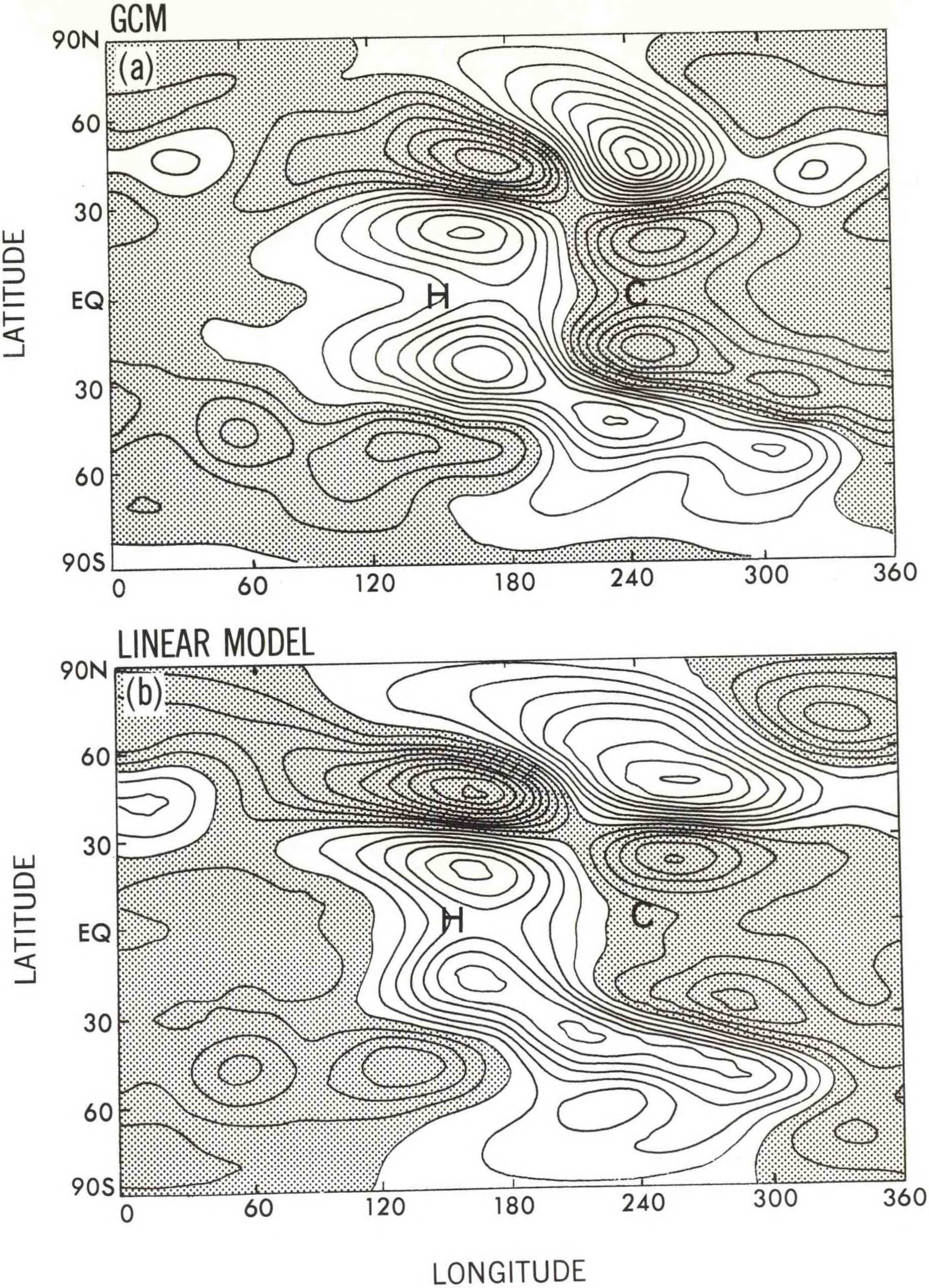

Fig. 1.7 300 mb eddy geopotential response to anomalous equatorial heating in the a) idealized GCM, and b) linear model. The centers of the heating and cooling anomalies are denoted by H and C, respectively. Contour intervals are 10 gpm.

1.8 ROSSBY WAVE DYNAMICS

S. Feldstein
J. Fyfe
I. M. Held
S. Lee
P. Phillipps

ACTIVITIES FY88

1.8.1 Hadley Cell-Rossby Wave Interactions

The subtropical jet is maintained by a competition between the acceleration of the zonal flow by the Hadley cell and its deceleration by Rossby waves breaking in the subtropics after having propagated in from higher latitudes. An idealized barotropic model of this competition has been finalized and additional calculations performed. Emphasis has been placed on the dependence of the mean flow modification on the amplitude of the Rossby wave, the manner in which the strength of the Hadley cell effects this mean flow modification, and the instabilities that can result in this system.

1.8.2 Rossby Wave Breaking and Baroclinic Eddy Life Cycles

The analysis of the effects of meridional shear on the life cycle of baroclinic instabilities in a two-layer model has been completed. The observed asymmetry of the life cycle -- baroclinic growth followed by barotropic decay -- has been simulated in this model. Essential to this life cycle is the wave breaking in the upper layer of the model that is generated when the wave radiates meridionally into regions of small zonal winds. In the limit of small supercriticality, a critical latitude (at which the phase speed of the most unstable mode equals the zonal flow speed) is needed in the upper layer to produce this wave breaking; if a critical latitude does not exist, the wave tends to decay baroclinically rather than barotropically.

As the supercriticality increases, the wave breaking in the upper layer tends to occur before the wave reaches the critical latitude; indeed, it appears that a critical latitude is not needed to produce breaking and a realistic life cycle. This result has motivated a study of Rossby wave breaking in the absence of a critical latitude. When a wave propagates into a region of small zonal winds, but where no critical latitude exists, how small need the zonal winds be, or how large the wave, for irreversible mixing to occur? When is there significant reflection from this breaking region? Calculations are being performed with a high resolution barotropic model to study these questions.

1.8.3 Transient Eddy Fluxes in a Two-Layer Model

An efficient two-level quasi-geostrophic channel model has been constructed for quantitative studies of the parameter dependence of baroclinic eddy fluxes. Preliminary calculations have been performed determining the model's sensitivity to the strength of the surface friction and to the width of the baroclinically unstable region.

PLANS FY89

Rossby wave breaking in the presence and absence of critical layers will be studied in a high resolution barotropic model.

Results from the two-layer quasi-geostrophic model will be used to test hypotheses concerning baroclinic equilibration and eddy flux closure schemes. The transition from one to two storm tracks that occurs when the width of the unstable region is increased will be isolated and analyzed.

A two-layer fully spectral model on the sphere will be constructed to study the abrupt transition, observed by M. Suarez (NASA Goddard) in a grid point model, from a realistic climate into a climate with strong superrotation in the upper tropical troposphere. A similar transition to that found by Suarez has been observed in the two-layer model used for ice-age studies (described in Section 1.6), where it can be induced by varying the surface friction. An attempt will be made to develop idealized models of this transition.

1.9 ENERGETICS OF TRANSIENT WAVES

D. G. Golder   J. Sheng
Y. Hayashi

ACTIVITIES FY88

The hemispheric atmospheric energetics in the frequency domain have been studied using observed data sets and those simulated by a GFDL general circulation model (ko, kp). Good agreement on the direction of energy flows exists between the observed and simulated data sets. The conversion from available potential energy (APE) to kinetic energy (KE) is the major direction of energy flow for all the frequency bands. In particular, this conversion is a major source of the KE for both tropical and extratropical low frequency oscillations. Through nonlinear interactions, high frequency motions (periods shorter than 10 days) gain APE from, and lose KE to the low frequency motions (periods longer than 10 days but shorter than the annual cycle). The nonlinear energy exchanges are relatively more important for the energy balance of low frequency modes. Both high and low frequency transients extract APE from, and supply KE to the time mean flow.

PLANS FY89

The atmospheric energetics in the frequency domain for observed and simulated data will be completed.

1.10 TROPICAL INTRASEASONAL OSCILLATIONS

D. G. Golder S. Miyahara
Y. Hayashi

ACTIVITIES FY88

The propagation and structure of the tropical intraseasonal oscillations have been studied by the use of a three-dimensional linear response model and compared with those obtained from the FGGE data (847). It is assumed that the imposed thermal forcing oscillates with a 40-day period and propagates eastward. Although the amplitude of the forcing is assumed to be large over a certain longitude band and small elsewhere, the resulting zonal wind oscillation has significant components that propagate eastward around the earth as observed. This oscillation is also associated with an observed longitudinal node in the region of the maximum forcing. When the imposed forcing is strictly confined over certain longitudes, the zonal wind oscillation propagates eastward and westward away from the forced region as in the case of a two-dimensional model. The eastward moving wavenumber 1 component is associated with the observed wave pattern of the combined Kelvin-Rossby mode in the upper troposphere, while it is dominated by that of the Rossby mode in the lower troposphere.

Analysis of a 21-wavenumber spectral GCM indicates that both 40-50 and 25-30 day spectral peaks in the zonal wind appear in the model even in the absence of the model's zonal variation at the surface. This result suggests that the deficiency in the amplitude of the 40-50 day period oscillations simulated by the model is not related to a geographical effect.

PLANS FY89

The study of tropical intraseasonal oscillations by the use of a GCM will be continued.

1.11 GRAVITY WAVE DRAG

D. G. Golder Y. Hayashi

Analysis has been made of the momentum and heat balance of GCMs with and without parameterized gravity wave drag. It was found, in particular, that the Ferrel cell circulation was significantly reduced by the effect of gravity wave drag. This reduction is not only due to the increase of mean friction but is also due to the reduction in the meridional flux of momentum associated with eddies which are damped by gravity wave drag.

PLANS FY89

The study of parameterized gravity wave drag in the GCM will be continued.

1.12 RADIATIVE TRANSFER MODEL INTERCOMPARISON STUDY

S. B. Fels V. Ramaswamy
S. M. Freidenreich M. D. Schwarzkopf

ACTIVITIES FY88

The new high-accuracy longwave radiative operational model has been completed. The results from the algorithm are compared to the reference line-by-line (LBL) calculations obtained for the first phase of the ICRCCM (Intercomparison of Radiative Codes in Climate Models). The comparison indicates that the new operational model is substantially more accurate than the operational models presently in use in the Laboratory.

Results of several of the benchmark longwave, line-by-line calculations made for the first phase of the ICRCCM are now available on magnetic tape. Several users outside GFDL have been provided with this tape for testing the accuracy of their radiation parameterizations.

The second phase of the ICRCCM investigation, involving the interaction of solar radiation with water vapor and cloud drops, was pursued. Very high frequency resolution (LBL) calculations of the absorption by water vapor were carried out for all the ICRCCM cases. The fluxes and heating rates over every 1 cm^{-1} interval have been saved on tapes for use by the scientific community. The commonly used Lacis-Hansen (L-H) parameterization was found to underestimate seriously the absorption in the upper troposphere and lower stratosphere (<300 mb); in general, there is an underestimation in the entire troposphere (Fig. 1.8). Based on the LBL results, improvements were made to the parameterization. The modified parameterization (modified LH) has been tested out for all atmospheric profiles, and for several zenith angles and surface albedos. The excellent agreement obtained renders the formulation suitable for use in climate models.

Benchmark calculations for the interactions involving liquid drops only were performed for the ICRCCM cloud specifications using the most accurate technique (doubling-adding method or DA). A high resolution in frequency space was found to be essential for the accuracy of the cloud radiative properties. The delta-Eddington method was found to be an economical and, in most cases, a good approximation for computing the cloud radiative properties.

The most complicated stage is the benchmark calculations involving simultaneous interactions with vapor and liquid phases. The 'exact' (LBL+DA) computations across the entire solar spectrum take up about 100 hours on the Cyber 205 for each cloud case. Ultimately, these benchmarks are necessary in order to obtain the most accurate estimates for the heating rates in a cloudy atmosphere and, thus, to form the basis for cloud radiation parameterizations. So far, it has been possible to perform only one of the ICRCCM cases. GFDL is the only institution to have undertaken this significant task.

Despite the limitation noted above, work has progressed on performing the 'exact' calculations for limited frequency intervals and to compare the LBL+delta Eddington (approximate) calculations over these intervals. An optically thin high (cloudtop at 180 mb; frequency interval 7300-7400 cm^{-1})

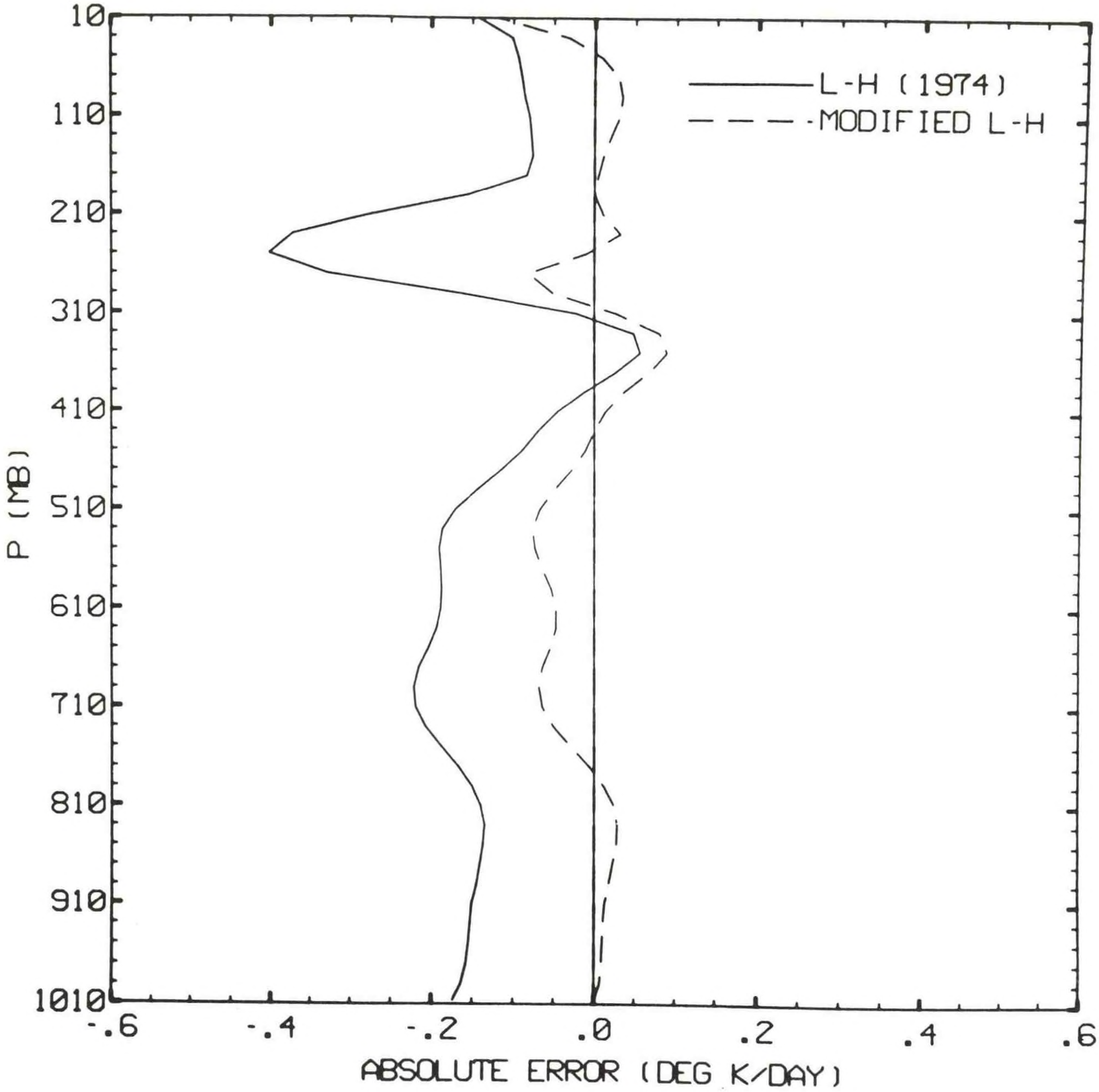

Fig. 1.8 Absolute errors in the solar heating rates (parameterization-line-by-line) due to water vapor absorption in the midlatitude summer atmosphere for the Lacis-Hansen (L-H) and the modified Lacis-Hansen (present study) parameterizations. Solar zenith angle is 30 degrees while the surface albedo is 0.2.

and an optically thick low cloud (cloudtop at 800 mb; frequency interval 10500-11000 cm^{-1}) were considered. The approximate calculations agree well in terms of the absorbed flux; however, the reflection is overestimated when the delta-Eddington method is used. Similar calculations have also been carried out by the radiation group at the Goddard Space Flight Center; the GFDL and the Goddard results are virtually identical, thus confirming the accuracy of the algorithms for the 'exact' calculations.

PLANS FY89

The new longwave radiative algorithm will be incorporated into existing general circulation models within the laboratory, and into the NMC MRF model.

A full documentation of the methods and results associated with the solar ICRCCM investigations is in preparation. The improved modified L-H parameterization will be implemented in the SKYHI GCM. The benchmark computations (LBL+DA) for the rest of the ICRCCM cases will continue. An alternative technique (pseudo-benchmark), which, while being computationally more efficient, yields results that differ only negligibly from the 'exact' benchmark results, will be developed. The solar spectrum calculations for the cases in which molecular absorption and/or cloud extinction are approximated will be compared against the pseudo- and, wherever possible, the 'exact' benchmark results. These results will constitute a basis for radiation parameterizations in cloudy atmospheres and should benefit the weather and climate modeling community.

2. MIDDLE ATMOSPHERE DYNAMICS AND CHEMISTRY

GOALS

* To understand the interactive three-dimensional radiative-chemical-dynamical structure of the middle atmosphere (10-100 km), and how it influences and is influenced by the regions above and below.

* To understand the dispersion and chemistry of atmospheric trace gases.

* To evaluate the sensitivity of the atmospheric system to human activities.

2.1 ATMOSPHERIC TRACE CONSTITUENT STUDIES

C. Black* S. C. Liu**
W. Chameides* J. D. Mahlman
H. Levy II W. J. Moxim

* Georgia Institute of Technology
** Aeronomy Laboratory/NOAA

ACTIVITIES FY88

2.1.1 Reactive Nitrogen in the Troposphere

A global transport model, previously used to study the behavior of North American nitrogen emissions (840), is used to simulate the transport and deposition of the global emissions from fossil fuel combustion (jy). See Fig. 2.1 for total yearly wet deposition and yearly average mixing ratios at 990 mb and 500 mb. The global parameter for wet deposition is based on observed deposition over North America and the dry deposition coefficients are calculated from observed surface concentrations and deposition velocities. The simulated wet deposition in Europe and at more remote sites in the Northern Hemisphere, as well as the simulated surface concentrations and their seasonal variation over the North Pacific, agree well with available observations. This study finds that, just as for dust, Asia is the major source of soluble nitrogen over the North Pacific; that European emissions dominate Arctic haze, particularly in the lower troposphere; and that emissions from fossil fuel combustion account for 10% or less of the soluble nitrogen observed at remote locations in the Southern Hemisphere. Injection from the stratosphere (379) appears to play a major role in the nitrogen budget of the Southern Hemisphere.

The same global model for combustion nitrogen is used to simulate the concentration of reactive nitrogen species at Hawaii. The simulation agrees well with recent observations of HNO_3 + NO_3 at Mauna Loa, both in magnitude and seasonal variation, and identifies the U.S. as the main source in the late summer and fall and Asia as the main source in the spring.

A detailed analysis of the transport mechanism producing the August NO_y maximum at Mauna Loa has been completed. The Mauna Loa combustion nitrogen is not simply advected near the surface southwestward to Hawaii from Southern California, as originaly hypothesized, but instead results from a complicated interaction of dry convection and synoptic scale 3-D flow.

Backward trajectories from Hawaii on either model pressure or isentropic surfaces were insufficient to explain the transport. A fully model-consistent 3-D trajectory package was developed which revealed that the transport originated in the "free troposphere" along a path from Northern Baja to the Texas gulf coast. Combustion nitrogen from the Southern California and Texas gulf coast source regions is advected at the surface towards the arid areas of Baja, the desert southwest, Northern Mexico and West Texas. Dry convection then vertically mixes the air to heights of 800 to 650 millibars where the subsiding wind flow from the east-northeast transports the NO_y to Hawaii.

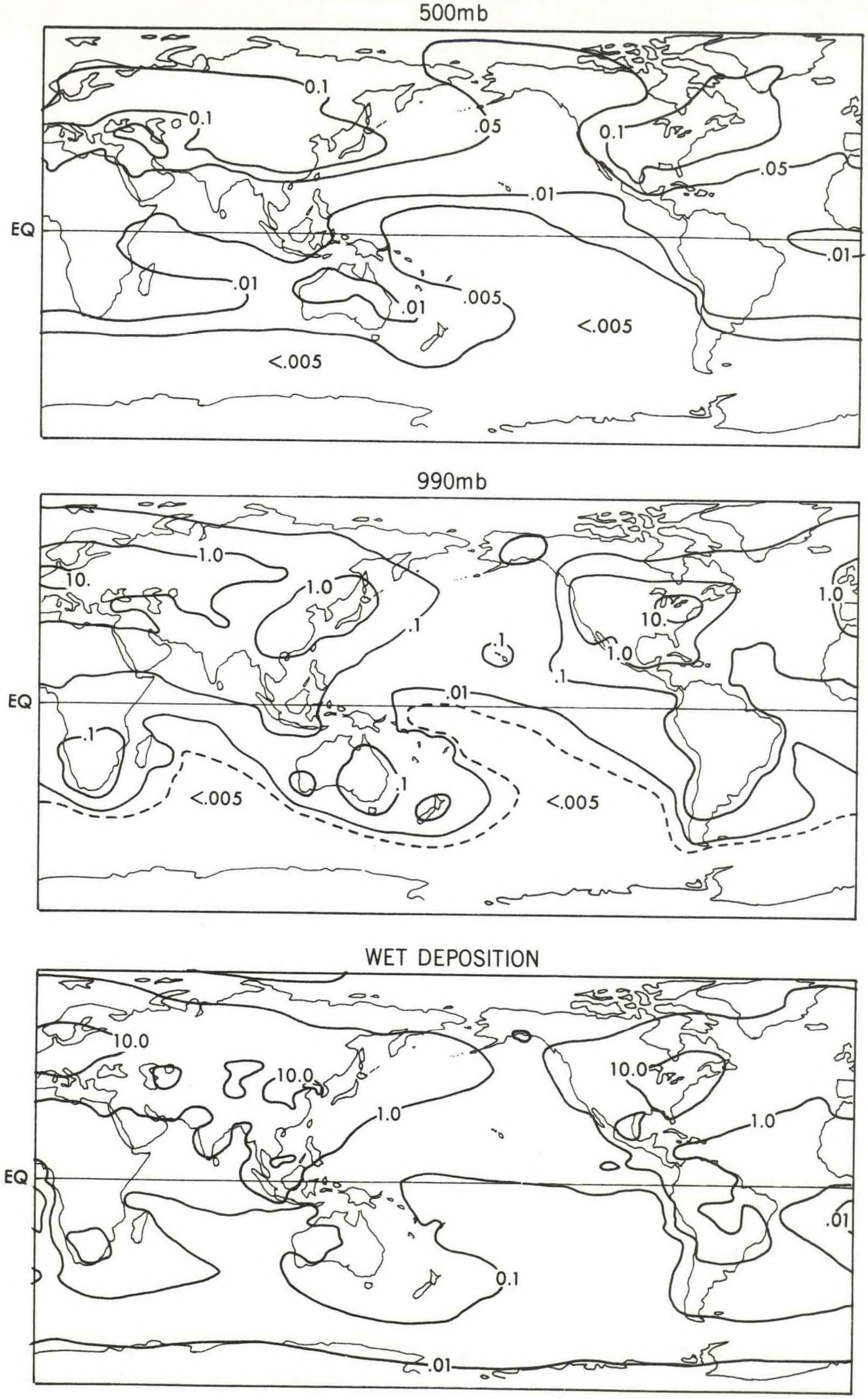

Fig. 2.1 Latitude-longitude plots of the yearly average of combustion NO_y mixing ratio (ppbv) at 500 mb in the middle troposphere and at 990 mb in the surface layer, and of the total wet surface deposition of nitrogen (m Mole m^{-2} yr^{-1}). Data is taken from the GFDL 3-D tracer model.

2.1.2 OH Lifetime Experiment

The time series for an inert tracer generated by the global transport model was used to generate transport coefficients for the Georgia Tech box model. It was found that the coefficients were insensitive to the troposphere-stratosphere exchange time, that a 3 year time series would be sufficient for the OH concentration determination and that assumptions of globally uniform OH were adequate for lifetimes longer than 6 years. The coefficients resulting from the model time series were twice as large as those based on observed time series in the tropics and ½ as large in mid-latitude.

PLANS FY89

The combustion nitrogen experiment will be run with U.S. sources only to aid in assessing the relative contributions of U.S. and Canada sources to deposition over Canada.

A series of multiple tracer experiments (the pure transport set of Rn, Pb and Be; the three classes of nitrogen species; SO2 and SO4) will be initiated. The specialized computer codes needed to analyze these experiments will be written. A simplified nitrogen chemistry will be developed for three classes of nitrogen compounds (insoluble inorganic oxides, soluble acids, organic nitrates) and the impact of this chemistry on the global transport of combustion nitrogen tested. The role of emissions from biomass burning on the global nitrogen budget will also be studied.

The analysis of synoptic transport of combustion nitrogen by baroclinic midlatitude cyclones will be completed. The main emphasis will be the effect of different storm systems on the tracer mixing ratio and wet deposition at various locations near and away from source regions.

Parameterizations for wet and dry removal as well as a treatment of both gas phase and heterogeneous chemistry will be developed for a regional to global model of sulfur. Both combustion emissions and biogenic sources will be developed.

A global model for CO will be started, either using the existing global transport model, or developing a new model based on the GFDL SKYHI model (2.2). The model test of the OH lifetime experiment will be continued using a reactive tracer with a 1-5 year lifetime.

2.2 MODELS OF THE TROPOSPHERE-STRATOSPHERE MESOSPHERE

S. B. Fels
K. P. Hamilton
H. Kida
J. D. Mahlman
J. Pinto
V. Ramaswamy
R. Saravanan
M. D. Schwarzkopf
R. Sneider***
X. Tao
L. J. Umscheid
X. Zhu

*** University of Utrecht, The Netherlands

ACTIVITIES FY88

2.2.1 Model Improvements

Continuing enhancements were added to the SKYHI GCM concerning model efficiency, structure, and documentation. Special emphasis was directed toward configuring the model to allow calculation of a "complete" ozone chemistry including the required precursor, reservoir, and reactive gases. The SKYHI model is now designed to run a number of transported trace constituents as well as account for a higher number of non-transported subspecies.

2.2.2 Higher Resolution Seasonal Cycle Experiments

The seasonal cycle of the middle atmosphere is being investigated with 3° and 1° latitude versions of the 40-level SKYHI model. The 3° version has been integrated for about 5 years, while the 1° version has completed over half of one year.

As reported earlier, the 1° model has produced a realistic major sudden warming in the middle stratosphere. The sudden warming onset was associated with a large transient burst of vertical component of "Eliassen-Palm flux" into the polar lower stratosphere. Further analysis of this model event has revealed a plausible physical connection that explains the observed correlation between tropospheric "blocking" events and stratospheric warmings. High amplitude block onsets are characterized by high latitude anticyclonic flows. Such events are located such that they are accompanied by large transient eddy heat flux into the polar cap. This corresponds directly to a burst of "Eliassen-Palm flux" into the polar cap, thus producing the requisite body force to slow down the stratospheric winds and produce its concomitant polar warming.

The 3° SKYHI model 5-year integration has produced, for the first time, an equatorial quasi-biennial oscillation (QBO) that bears some resemblance to the observed. The model QBO has a peak-to-peak zonal wind amplitude that is about a quarter of the observed. Significantly, however, its period (varying from 24-48 months) is quite realistic. The simpler models often have great difficulty in predicting the proper period. This suggests a possibly more robust QBO period determining mechanism that may have been overlooked in previous theoretical models.

2.2.3 Sources of Systematic Errors in SKYHI Climatology

An ongoing analysis of systematic SKYHI errors is directed toward identification of missing or inappropriately parameterized physical processes in the model. The 1° latitude version of SKYHI shows a typical pattern of excessive zonal westerly flow. Interestingly, in contrast to other high resolution models, the overly strong westerlies are confined to the surface layer. Thus, for this model the typical choices for gravity wave drag parameterizations appear to be inappropriate. Much further work will be required to clarify the issue. The model shows a cold bias that extends into the lower stratosphere. Recent ozone measurements from the GMCC network suggests that the SKYHI prescribed ozone fields have been underestimated, especially in the lower latitudes. This effect alone may account for an important fraction of the cold bias.

2.2.4 Evaluation of the Simulated SKYHI Gravity Wave Field in the Middle Atmosphere

The simulated winds and temperatures in the middle atmosphere of the SKYHI model display a great deal of relatively small-scale, high-frequency variability. Much work at GFDL over the last few years has focussed on analysis of the space-time spectrum of this variability. The results of these studies have been interpreted as showing the existence of a broad range of vertically-propagating gravity waves in the model (743, ip).

Over the last year this aspect of the model simulation has been examined from a rather different perspective. In particular, the character of instantaneous vertical profiles of the horizontal wind have been studied. These typically display a clockwise polarization with height in the Northern Hemisphere and a counterclockwise polarization in the Southern Hemisphere. This result is consistent with the existence of vertically-propagating gravity waves of sub-inertial period. The qualitative character of these profiles is similar to that typically seen in rocket soundings of the stratospheric wind. Work is now underway to perform a detailed quantitative comparison of the statistical properties of the available rocket observations with those of the model simulation.

2.2.5 Analysis of the SKYHI Semiannual Oscillation

An investigation of the 3° SKYHI model simulation of the semiannual oscillation (SAO) of the tropical upper stratosphere and mesosphere has now been completed. As noted in last year's report, the simulated amplitude and phase of the SAO in the upper stratosphere are in very good agreement with observations (see Fig. 2.2). The westerly mean flow acceleration near the tropical stratopause in the model was shown to be caused largely by wave-driving from relatively small-scale, vertically propagating gravity waves.

Over the past year, further analysis has shown that the equatorially-trapped form of the westerly SAO acceleration is largely a consequence of a similar modulation of the gravity wave flux emerging from the tropical troposphere. However, the seasonal modulation of the stratopause accelerations is very different from that of the tropopause gravity wave flux. In particular, the SAO component of the stratopause mean flow accelerations is

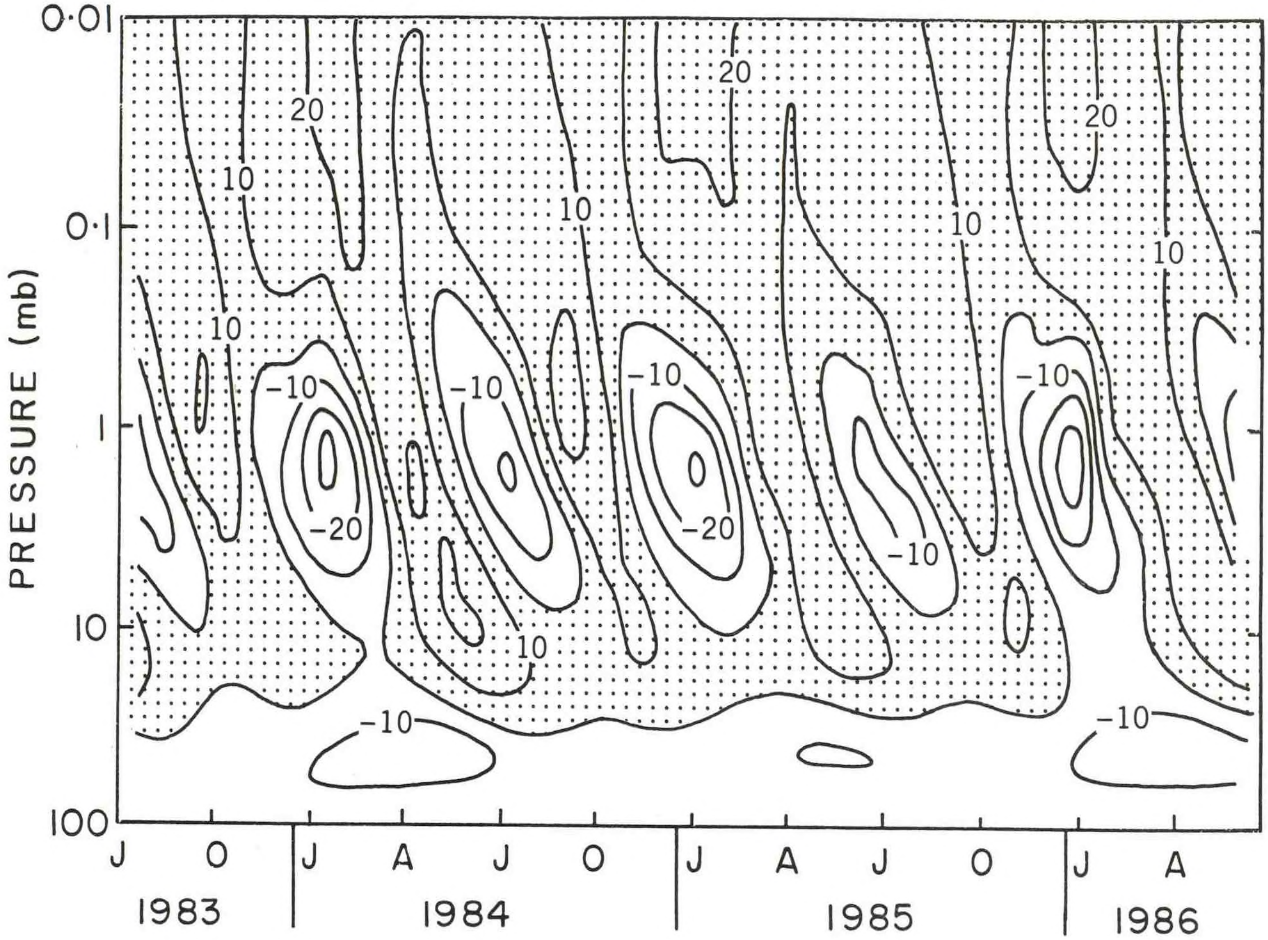

Fig. 2.2 Equatorial zonal-mean (m s^{-1}) from 100-0.01 mb pressure levels in the 3° latitude resolution "SKYHI" GCM. Contours are for monthly mean data from model astronomy years "1983" to "1986".

almost absent in the gravity wave flux at the tropopause. Details can be found in (jm).

2.2.6 Lagrangian Analysis of Stratospheric Wave Breaking

The first major phase of a project to investigate stratospheric disturbances from a Lagrangian trajectory perspective has now been completed. Detailed calculations of particle cluster trajectories have been calculated for the 1° latitude SKYHI model sudden stratospheric warming case described in 2.2.2 above. Particles within the cyclonic solar vortex show very small irreversible dispersion. At the edge of the vortex and beyond extraordinarily high dispersion rates are obtained, demonstrating the fundamental validity of the recent "surf zone" and wave breaking ideas of McIntyre and Palmer.

In the anticyclonic shear zones outside the polar vortex, isentropic versus three-dimensional trajectories show remarkable differences on time scales less than 10 days. This strongly suggests that, even on comparatively short time scales, non-isentropic processes must be considered carefully in Lagrangian analysis of stratospheric wave dynamics.

2.2.7 Isentropic Coordinate Potential Vorticity Diagnostics

Recent theories of stratospheric motions have illustrated the power of using isentropic-coordinate diagnostics of potential vorticity behavior to clarify understanding of dynamical behavior. To explore some of these possibilities, the SKYHI isentropic-coordinate diagnostic package has been adapted for potential vorticity analysis of sudden warming events.

Although the analysis is in the early stages, some aspects of the role of non-conservative processes in changing and maintaining potential vorticity structure have been investigated. In particular, the diagnostic insights achieved appear to depend in rather subtle ways upon the particular formalism chosen for describing non-conservative processes. For example, what appears to be the most physically based formalism gives a production rate for polar cap potential vorticity that is significantly faster than expected from the recent arguments of Haynes and McIntyre. This suggests that the polar vortex is more susceptible to mid-winter mixing and diabatic processes than recently assumed.

2.2.8 Planetary Wave Propagation in the SKYHI Model

The study of planetary waves in the stratosphere using linear quasi-geostrophic models is being continued. The results from steady-state models showed that the structure of stratospheric waves is mostly determined by the zonal wind configurations, while their amplitude depends on both the amplitude and phase speed of the tropospheric forcing.

However, there are still significant discrepancies between results from the linear steady calculations and the GCM planetary wave behavior. In order to understand this, a time-dependent, quasi-geostrophic, single wave mean-flow interaction model was constructed and is currently being tested.

2.2.9 Simple Radiative-Symmetric Models

The details of an elementary model simulating the response of a geostrophically balanced vortex to a transient radiative forcing has been completed (jc). This work provides a simple way of understanding the manner in which heating is partitioned between temperature change and vertical motion. The analytic results are complemented by several representative numerical integrations. These are of particular use in putting bounds on the possible size of the radiatively induced upward motion during the antarctic spring, and show that this effect should be of negligible importance for the seasonal ozone hole.

2.2.10 Mechanistic Models of the Quasi-Biennial Oscillation

Current understanding of the quasi-biennial oscillation (QBO) of the zonal winds in the equatorial lower stratosphere is based on the simple one-dimensional linear model due to Holton and Lindzen. However, their assumption of a discrete two-wave forcing may be too restrictive. An extended model has been developed to study the effects of forcing by a very large ensemble of waves. This multi-wave model also includes a simple parameterization of the effects of vertical advection due to the Hadley circulation. Integrations with this model indicate that a variety of shapes of the wave forcing spectrum can produce long period QBO-like oscillations. Also, the mean rising motion near the tropopause appears to provide a natural lower boundary condition for these oscillations. The amplitude and period of these oscillations seem to be related to the shape of the wave forcing spectrum and the vertical advection profile in a complex, and interesting, manner.

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The 1° resolution SKYHI model will be integrated further and investigated in greater detail. Topics will include tropospheric phenomenon, wave breaking, potential vorticity budgets, Lagrangian transport and wave-mean flow interaction. Analysis of the impact of gravity waves as well as the dynamics of the semi-annual oscillation and the quasi-biennial oscillation will continue.

A new phase of model development will be initiated with emphasis on trace constituent chemistry transport, cloud processes, radiative transfer, and subgrid-scale parameterizations.

2.3 PHYSICAL PROCESSES IN THE MIDDLE ATMOSPHERE

S. B. Fels
S. C. Liu**
J. D. Mahlman
C. C. Ma
J. Pinto
V. Ramaswamy
M. D. Schwarzkopf
L. J. Umscheid
X. Zhu

** Aeronomy Laboratory/NOAA

ACTIVITIES FY88

2.3.1 Modeling of Ice Phase in the Polar Stratosphere

A one-dimensional stratospheric model with ice microphysical processes was developed to study the evolution of an ice particle size distribution in the polar stratosphere during the Antarctic winter (875). The critical temperature for water vapor to be deposited as ice at any altitude depends on the vapor mixing ratio as well as on the curvature of the nuclei. As temperatures decrease below the frost point, particles grow and gravitational settling occurs. The magnitude of temperature decreases and the existence of favorable ice nuclei are found to be principal factors. The sustained decrease of temperatures during the austral winter (especially within the polar vortex) leads, in the limit of weak latitudinal mixing, to a loss of water vapor from the stratospheric altitudes through the growth-cum-sedimentation processes. The observed temperatures (1980-1987) for the South Pole region indicate that the dehydration process was probably operative in the stratosphere during each winter. The dehydration of the stratosphere implies that soluble chemical species may also be lost irreversibly, especially at the altitudes of relevance to ozone, and could, therefore, be a significant casual factor in the "ozone hole" phenomenon.

2.3.2 Ozone Photochemistry

A self-consistent ozone photochemistry code has now been incorporated into the SKYHI model. The code management of the basic chemically relevant processes of advection, photodissociation, and kinetics are now performing in a fully three-dimensonal (3-D) manner in SKYHI. The chemistry itself still has problems, including the self consistent modeling of the reactive hydrogen diurnal cycle and its parameterization. A rescaling of the equations for more appropriate application to the 3-D atmosphere has been explored.

2.3.3 Observational Study of the Ozone Quasi-biennial Oscillation

The quasi-biennial oscillation (QBO) has been examined in observations of total column ozone from several tropical stations. The ozone QBO at Manua Loa (19.5°N) was found to have a remarkable synchronization with the annual cycle. Both positive and negative ozone extremes were found to almost always occur between December and March. It was shown that the annual cycle-QBO phase locking is much more pronounced for the ozone record than it is for the familiar QBO in prevailing tropical stratospheric winds. This result has been taken as evidence that the dynamical QBO acts to modulate a strong seasonal transport of ozone into the tropics associated with planetary waves of extratropical origin. Details are given in (kl).

PLANS FY89

The one-dimensional multi-layer microphysical model will be linked with a radiative transfer model to study the interactive effects of microphysics and radiation in the polar winter stratospheres. The results from the one-dimensional modeling efforts will be used to construct ice phase parameterizations for the SKYHI GCM; these, in turn, should prove useful in modeling the equatorial tropopause regions and the winter polar stratospheres. The long term project to develop a fully consistent three-dimensional ozone chemistry in the SKYHI GCM will continue. This will be coupled with a longer term effort to prepare a new generation tracer transport model out of the SKYHI framework.

2.4 EFFECTS OF ANTHROPOGENIC CHANGES IN ATMOSPHERIC COMPOSITION

S. B. Fels
J. D. Mahlman
J. Pinto
V. Ramaswamy
M. D. Schwarzkopf
L. J. Umscheid

ACTIVITIES FY88

2.4.1 Antarctic Ozone Depletion

A hypothesis has been advanced that a significant fraction of the 1979-1987 October Antarctic ozone reduction could be due to natural dynamical mechanisms (753). It was noted in (GFDL Activities FY87, Plans FY88) that GFDL radiative calculations suggest that the transient vertical lifting may not be sufficiently strong to explain the observed magnitude of ozone decrease. The recent aircraft expedition out of Puerta Arevas, Chile, strongly confirms this, but further offers strong evidence that the ozone reduction is mainly attributable to a direct chemical destruction through an extremely efficient chlorine catalysis process.

2.4.2 Seasonal Doubled CO_2 Experiment

The very large inter-annual variability in the response of the lower stratosphere to altered radiative forcing requires that a multi-year GCM integration be carried out to assess the probable effects of doubled CO_2. The 3° resolution version of the seasonal SKYHI model has now been integrated for three fall and winter seasons with 660 ppmv CO_2. In each case, the initial conditions are taken from a different model year 1X CO2 control run on October 1.

Results from the three runs for December show unexpected and consistent changes in the stratospheric thermal response, with temperature changes in the polar night lower stratosphere being smaller than predicted by purely radiative considerations. This is at variance with what is expected on the basis of simple mechanistic models, and is especially surprizing in view of the tendency of the SKYHI model to be overly radiative in this part of the atmosphere. In the tropical stratosphere, the GCM results appear to be basically in agreement with the predictions of the earlier coarse resolution annual average GCM results reported by Fels et al. (431).

2.4.3 Climatic Effects Following a Nuclear War

The effects of the longwave properties of soot in the aftermath of a nuclear war were studied by incorporating a gray-absorber approximation in the longwave radiative transfer algorithm of the N30 SKYHI model discussed in (GFDL Activities FY87, Plans FY88). Simulations were performed with and without the longwave absorption due to aerosol injections in the 30-70°N belt, starting from September 30 of a model year. The principle result is that surface coolings are not as enhanced when the aerosol longwave properties are considered. At 60°N, the decrease in the land surface temperature on Day 6 without the aerosol longwave absorption is 19K; this is reduced to 11K with the inclusion of the longwave absorption. On Day 12, these values become 16 and 10K, respectively. These findings are qualitatively similar to an earlier study of the short-term simulations (ii). In the present simulation, the change in land surface temperature at 60°N after a month is small both with and without the longwave absorption. Simulations for summer conditions (starting from June 30) have also been performed with the aerosol longwave absorption included. On Day 12, the decrease of land surface temperature at 60°N is 20K, which exceeds the cooling for the Fall simulation mentioned above.

PLANS FY89

A SKYHI simulation will be started of the chemical radiative-dynamical response to a parameterized Antarctic ozone "hole" loss. The doubled-CO_2 experiment will be run to completion and analyzed in further detail.

Analysis of the completed runs will be begun, and the model integrated through several more winters with 2X CO_2, in order to provide a larger statistical sample.

A comparative analysis of the Fall and Summer Nuclear War simulations will continue. In addition, a Winter simulation will be performed and analyzed. Sensitivities with respect to altitude of initial injection and that due to water vapor will be conducted.

3. EXPERIMENTAL PREDICTION

GOALS

* To develop more accurate and efficient atmospheric and oceanic GCM's suitable for monthly and seasonal forecasting.

* To identify external forcing mechanisms important in the forecast range of several weeks to several seasons, and to develop means of accurately specifying the initial states of atmosphere, ocean, soil moisture and snow/ice cover.

* To investigate the influence of processes such as orographic forcing, cloud-radiation interaction, cumulus convection, and soil moisture anomalies on atmospheric variability.

3.1 CLIMATE OF THE ATMOSPHERE

P. L. Baker
J. Derber
C. T. Gordon
R. T. Pierrehumbert
V. Ramaswamy
M. D. Schwarzkopf
J. Sirutis
R. Smith
W. F. Stern
B. Wyman

ACTIVITIES FY88

3.1.1 Spectral Model

The development of an accurate and efficient model suitable for integration over the seasonal time scale is continued (828). The CPU efficiency is being improved by incorporating a semi-implicit scheme for the advection of vorticity and moisture, and the wall-clock time is also being reduced. An orographic gravity wave drag effect which utilizes a momentum-saturation profile (im) has been included. The cloud-radiation effect (801) has been incorporated in this model for the first time, but this is still in the experimental stage. A more appropriate lateral diffusion process has also been investigated. Erroneously weak westerlies over the Southern Ocean are being rectified.

3.1.2 Cloud-Radiation Interaction

A scheme for cloud-radiation interaction consisting of three elements has been developed. The primary element is the prediction scheme for fractional cloud amount, similar to that of J. Slingo[1]. The fractional cloud amount depends on the relative humidity and convective precipitation for clouds at all levels, while it also depends on the vertical motion and dry as well as moist static stability for low clouds. Second, there is a self-consistent treatment of cloud optical properties provided by the Climate Group. The third element is a parameterization of optical depth for non-precipitating cold clouds, a scheme proposed by Harshvardhan and Randall; for other clouds the optical depth is specified. The parameters of the various component schemes have been tuned, with moderate success, to obtain quasi-realistic earth radiation budgets and cloud amount fields.

3.1.3 Global HIBU Model

Considerable effort has been expended on improving the global version of the HIBU model. This model is essentially a global version of the LAHM model used by the Mesoscale Dynamics Group (hs and 845) and is being developed for use in a new data assimilation system. Improved physical parameterizations have been included in the model. The efficiency of the model has been substantially improved primarily through a speed up of the polar filtering. Also, various diagnostic and display routines have been developed.

[1]Slingo, J. M., 1987: QJRMS, 113, p. 899.

3.1.4 Orographic Effect

A scheme to parameterize subgrid-scale orographic gravity waves has been incorporated as a standard feature in the GCM. This parameterization incorporates non-linear theory for determining the base momentum flux escaping a low-level region and develops a vertical deposition profile based on convective wave breaking criteria. More details about the scheme may be found in (im). Extended range forecast results from northern hemisphere winter cases indicate a significant reduction in systematic zonal wind error in the upper troposphere and lower stratosphere, as well as a reduction in systematic mean sea-level pressure errors.

3.1.5 Comparison of Various SGS Parameterizations

The results of the diagnostic studies of A, E, and F SGS (subgrid-scale) parameterization packages (627) are being documented. The E-physics appears to be more capable of representing blocking ridges than the A-physics. The reason for this result is still unclear. The study shows that the simulation of Madden-Julian waves is unsatisfactory in all models using the current versions of cumulus parameterization.

An efficient Arakawa-Schubert convection parameterization code from the Naval Environmental Prediction Research Facility, Monterey, California, is being incorporated in the spectral model. At the same time, the correction of Tokioka et al.[2] for adequately representing the Madden-Julian wave is being adapted.

3.1.6 Land Surface Processes

The bucket method of soil moisture treatment has been modified from one layer to two layers. However, this scheme appears to be still inadequate for the realistic representation of ground temperature and soil moisture. Stomatal resistance and the canopy level water storage parameterizations may be necessary. The SIB (Simple Biosphere) model[3] is being adapted from the COLA (Center for Ocean-Land-Atmosphere Interaction) of University of Maryland.

3.1.7 Ocean Model

Several improvements to the ocean model have been made in the last year (iw). These improvements have included a limitation on the vertical mixing length scale to reduce mixing in stable regions (jt), an improved orography and the inclusion of a diurnal cycle in the radiation. These changes have reduced the climate drift of the ocean model. Several improvements to the model efficiency have also been made.

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[2]Tokioka et al., 1988: to appear in JMS, Japan.

[3]Sellers, P. J., et al., 1986: JAS, 43, 505-531.

PLANS FY89

The spectral model will be modified to use triangular truncation rather than rhomboidal truncation. A high vertical resolution spectral model (R21L72) will be developed. Enhancements and tests of physical parameterizations will continue. The improved Arakawa-Schubert cumulus parameterization, the cloud radiation interaction and SIB model will be examined in long GCM runs. The gravity wave drag parameterization will be modified to include a non-linearly enhanced low-level wave breaking zone. The step-mountain coordinate of Mesinger (hs) will be included in the global HIBU model. The improvement in the physical parameterizations will also be continued. Investigation will be undertaken to identify and hopefully eliminate systematic biases of the ocean model. Also improvements in the vertical mixing parameterizations will be made. The shallow convection scheme will be finalized. More flexible treatment of cloud overlap will be incorporated, in collaboration with the Climate Group. The cloud-radiation interaction plus shallow convection will be tested in a higher resolution GCM.

3.2 THEORETICAL AND DIAGNOSTIC STUDIES

J. Anderson
Y. Chao
R. Gudgel
K. Lamb*
S. J. Lin
E. Manzini
K. Miyakoda
F. Parham*
S. G. H. Philander
R. T. Pierrehumbert
A. Rosati
B. Wyman

*Program in Applied and Computational Mathematics

ACTIVITIES FY88

3.2.1 Theoretical Studies of Atmospheric Dynamics

The question of whether Ekman friction can suppress baroclinic instability has been investigated. Stability calculations have been carried out using a realistic boundary layer model and realistic wind profiles with both vertical and horizontal shear (jv). It was concluded that Ekman friction cannot stabilize the instability in the ocean storm tracks. This suggests an alternate mechanism for the sharp termination of the storm tracks.

Chaotic dispersal of tracer by superpositions of Rossby waves has also been studied. This project, which revealed the important role played by chaotic particle advection in the homogenization of tracers within closed gyres, has led to a novel mechanism for upscale energy transfer in eddy-blocking interactions. The study has also shown that even in smooth and deterministic flow fields, particle trajectories exhibit rapid loss of predictability.

Another investigation treated nonlinear stationary gravity waves in a compressible atmosphere. Calculations with a simple nonlinear oscillator model, which nevertheless permitted realistic background wind and temperature profiles, revealed that wave breaking occurs considerably higher than typically predicted by less sophisticated parameterizations, but nevertheless, low enough to have a marked effect on the upper troposphere and lower stratosphere. There are good possibilities to use this kind of model in order to improve gravity wave flux parameterization in large-scale general circulation models. Progress has also been made on the linear theory of gravity wave critical level interactions.

Finally, a new numerical method for solution of large instability problems has been developed and successfully applied to a problem in geophysical fluid dynamics. The method requires an order of magnitude less computer memory and computation time than older methods, and automatically yields only the most unstable modes. The method can be used to investigate storm track structure and large-scale barotropic instabilities associated with atmospheric low frequency variability.

3.2.2 Effect of Orographic Gravity Waves

The theoretical studies of gravity wave breaking and the momentum flux absorption have been reviewed. As a second step, Pierrehumbert's parameterization (im) is being investigated, using a high resolution two-dimensional (x-z) anelastic model (810). The objective is to understand the behavior of orographic waves, their interaction with the basic flow and turbulence characteristics.

3.2.3 Study of the 1982/83 ENSO

Following Part I (jw) of this study, Part II addresses the question of how the Southern Oscillation (SO) index swings from a positive to a negative value before the onset of El Nino. This aspect has been explored, using uncoupled GCMs separately for the atmosphere and the ocean. The conclusion obtained so far is that a certain anomaly pattern of sea surface temperature is favorable for the development of a negative SO index. Investigation is now focusing on the wind field with particular emphasis on characteristics for the development of a favorable sea surface temperature pattern, and on what the source may be for the wind field.

3.2.4 Twelve-Year Run of the Ocean GCM

To study the characteristics of the 1 deg. x 1 deg. and 15 level ocean GCM, a 12-year run from 1976 to 1987 is being undertaken. This period includes three El Ninos. A preliminary study over the period of 1979-1983 is being run. One of the current efforts is to improve the amplitudes of sea surface temperature variability and to correct biases such as cold water intrusion from the Labrador Sea to the Atlantic Ocean.

3.2.5 The OHC (ocean heat content) Study

The objective is to investigate a possible necessary condition for the onset of El Nino, in terms of the OHC. The ocean model is a simplified and economical version of Philander-Pacanowski (757). A 20 year period is being studied by applying the monthly mean observed winds from the GFDL Observational Studies Group (599) to this model. The evolution of OHC anomalies in the western Equatorial Pacific and their relationship to the ENSO phenomenon is being examined.

PLANS FY89

The two-dimensional model for the study of orographic gravity waves will be refined with respect to lateral boundary conditions, initial conditions, and spatial resolution. With regard to the ENSO study, the R30L9 model is being applied to the simulation of 1982/83 El Nino, specifying the lower boundary condition with the observed sea surface temperature. The results of the twelve year ocean GCM run will be diagnosed to investigate the causes for systematic errors in the ocean model.

3.3 DATA ASSIMILATION

J. Derber
W. Gudgel
J. J. Ploshay
A. Rosati
W. F. Stern

ACTIVITIES FY88

3.3.1 Ocean Data Assimilation

The global oceanic data assimilation system (iq) has been applied to surface data and vertical temperature profiles during the FGGE year (December 1978-December 1979). The results from the assimilation system have been quite encouraging. Comparison to independent sea surface temperature analyses shows that the assimilation system is able to capture all the major features of the surface temperature field. Subjective examination of subsurface fields have shown a reasonable depiction of the oceanic state, except the equatorial undercurrent. Many improvements to the assimilation system have been made in the last year including an improved orography, improved statistics and various improvements to the prediction model. Many efficiency modifications have also been made.

3.3.2 Development of a New Atmospheric Data Assimilation System

A new atmospheric four-dimensional data assimilation system is being developed for use with the global HIBU model. This assimilation system is based on variational principles and requires the development of an adjoint model. Considerable progress has been made on the development of this adjoint model but it has not yet been completed.

While the more complex system is being developed, two techniques for assimilating the data have been examined using a simple quasi-geostrophic model (800). A variational nudging technique which distributes corrections to the model solution over the assimilation interval has been developed and examined using this model. This technique consistently outperforms a variational fitting technique, which finds the least square fit model solution over the assimilation period ("the adjoint technique"). It is planned that both of these techniques will be implemented for use with the global HIBU model.

3.3.3 Re-analysis of Atmospheric FGGE Data

As was mentioned in (GFDL Activities FY87, Plans FY88), the re-analysis is underway. Three operational errors were found, related to the specified sea surface temperature, satellite temperature soundings, and the failure to toss-out some erroneous moisture data. For this reason, it was necessary to repeat some of the analysis. An archived tape has been sent to Dr. Salstein, Atmospheric and Environmental Research, Inc., MA for evaluation.

PLANS FY89

The atmospheric FGGE re-analysis will be continued. The ocean data assimilation will be extended beyond January 1980 and further improvement to the assimilation system will be made. The improvement to the oceanic assimilation system will concentrate on reducing the errors in the equatorial undercurrent and reducing the adjustment problem which occurs when the assimilation procedure is ended. Development of the new atmospheric assimilation system will continue. The problem of model parameter adjustment will be examined using the quasi-geostrophic system.

3.4 LONG-RANGE FORECAST EXPERIMENTS

T. C. Gordon
R. Gudgel
K. Miyakoda
A. Rosati
J. Sirutis
R. Smith
W. F. Stern

ACTIVITIES FY88

3.4.1 Monthly Forecast Study -- Control Runs

The current standard model with R42L18 resoluton has been frozen with respect to the subgrid-scale physics, and has been applied to one-month integrations for six cases, as specified by the WGNE (Working Group on Numerical Experimentation) of CAC/JSC, WMO and ICSU. The model includes the updated orographic gravity wave drag parameterization, fourth-order lateral diffusion, moist convective adjustment, the level 2.5 turbulence closure scheme, and a correction to the extension of orography over the ocean due to the Gibbs phenomenon. The effect of interactive clouds is the focus of another study.

3.4.2 Monthly Forecast Study -- Cloud-Radiation Interaction

The impact of cloud-radiation interaction on diabatic heating and the atmospheric dynamics is being investigated. Comparative 30 day integrations have been performed using an R21L18 GCM, both with and without the cloud-radiation interaction, for 3 winter and 3 summer cases. In the "control" experiments, zonal mean cloud amount fields and global mean cloud properties are specified. Analysis of the results is in progress. Results show that cloud-radiation interaction significantly enhances the longitudinal variation of short- and long-wave cloud forcing. In the ITCZ, the long-wave cloud forcing is qualitatively similar to observation, whereas the short-wave and net cloud forcing are too intense.

3.4.3 First Experiment Using an Air-Sea Model

The air-sea model has been applied to a seasonal forecast experiment for a single case starting at 1 October, 1979. The model consists of the atmospheric R21L9 or R30L9 model and the oceanic model (iw). The initial conditions for the ocean and the atmosphere were obtained from the four-dimensional data assimilation systems. One run is with the full system for the atmosphere and the ocean model system, and the second includes a Newtonian nudging toward the observed sea surface temperature. The experiments reveal that a strong air-sea interaction is evident, manifesting a close connection between the predicted sea surface temperature and the sea level pressure. The results are shown in Fig. 3.1 and 3.2. There is a certain degree of predictive skill, but an excessive cooling in the sea temperature over the entire oceans is quite evident. Also it may be seen in the wind field that the trades are underestimated and the roaring forties are missing.

3.4.4 The Systematic Bias in the Air-Sea Model Experiment

A dominant feature of the air-sea model is excessive cooling which takes place in the sea surface temperature over almost all of the oceans except the Southern Ocean (ju). Possible reasons for this cooling are: deficiencies of condensational heating due to the spatially low resolution atmospheric model; an adjustment problem in the oceanic initial conditions; and systematic biases of the atmospheric and oceanic GCMs. The cause of the errors in the equatorial zones, the midlatitude zones of strong ocean current, and the Indian Ocean are being investigated.

By adding a correction to the heat flux, a tentative remedy for the systematic error has been found. The skill scores obtained by using the correction to the heat flux represent a substantial improvement over the cases without it.

PLANS FY89

A Newtonian nudging to the observed sea surface temperature will be applied to the air-sea model from 1979 to 1983. This study will provide definitive information on the systematic deficiency in the heat flux which should prevent the excessive cooling. The causes of the biases in the atmospheric and oceanic GCM will be investigated. Analysis of the six case monthly forecast study of cloud-radiation interaction will be completed and an analogous intercomparison will be performed integrating the GCM in climate mode. Also, another monthly forecast study, focusing on the impact of shallow convection, will be initiated.

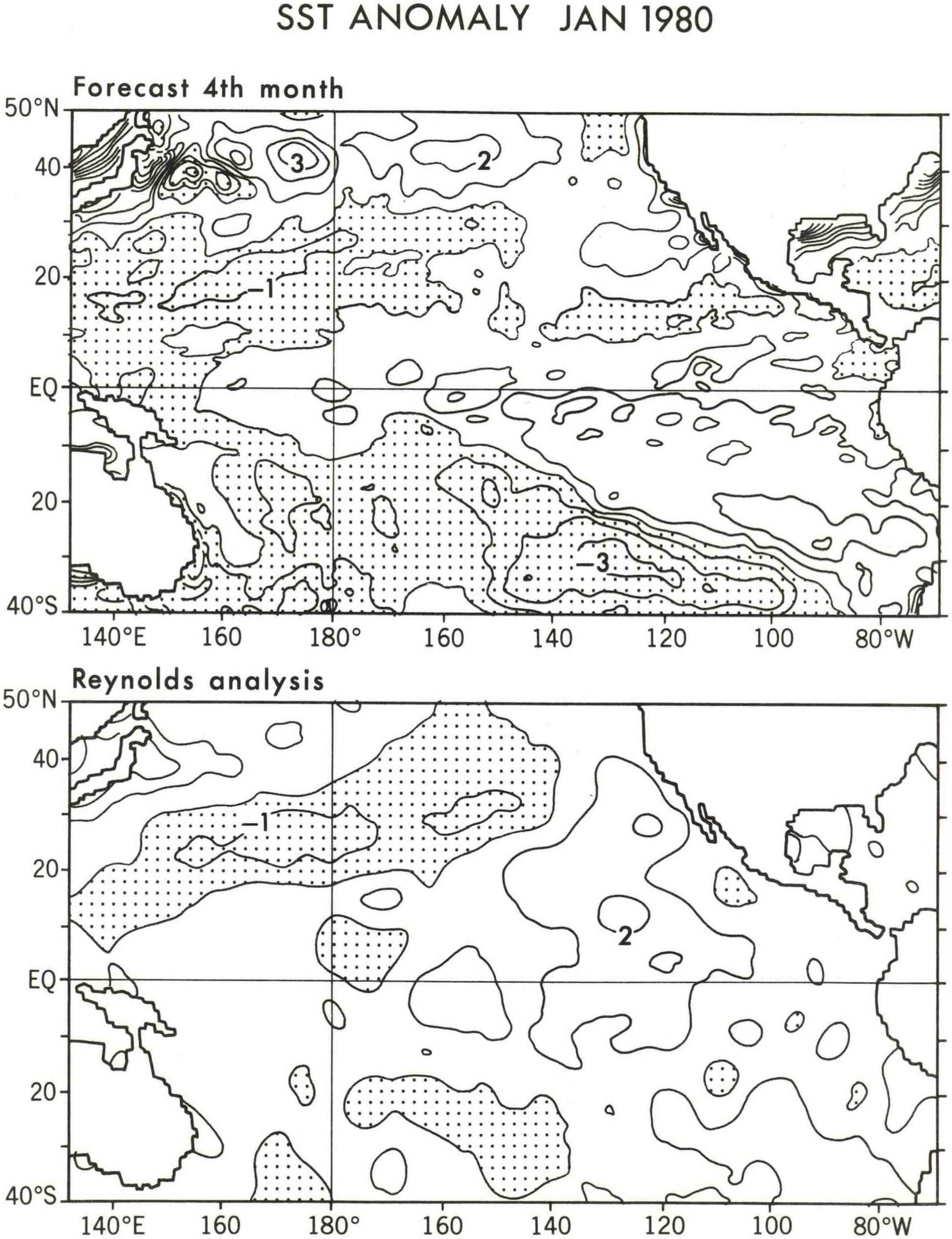

Fig. 3.1 The monthly mean sea surface temperature anomalies in the fourth month (January, 1980) of forecast (upper), compared with the NMC analysis (lower). Contour interval is 1°C. The negative anomalies are shaded.

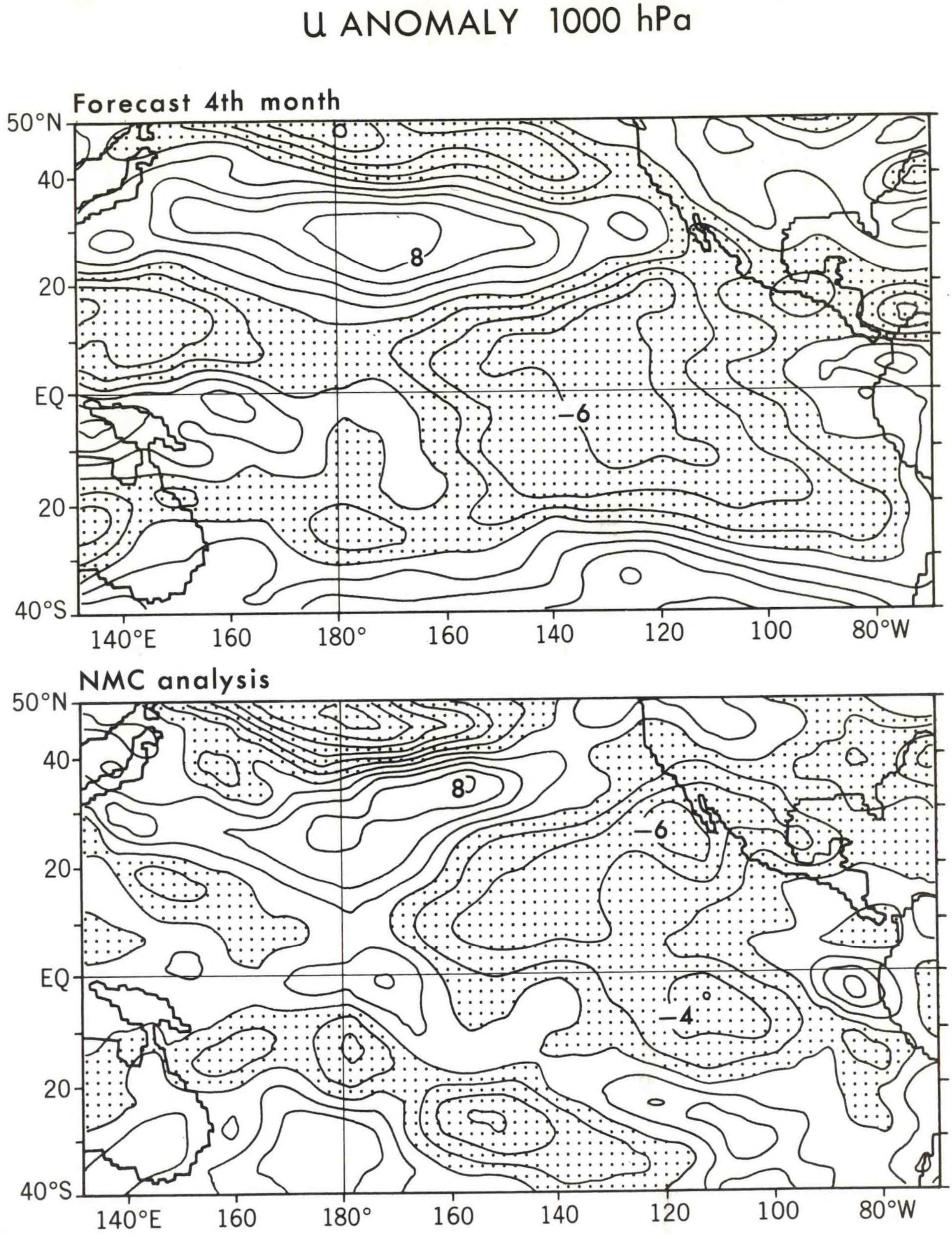

Fig. 3.2 The monthly mean zonal component of wind anomalies at 1000 hPa in the fourth month (January, 1980) of forecast (upper), compared with the NMC analysis (lower). Contour interval is 2 m s^{-1}. The easterly winds are shaded.

3.5 COLLABORATION WITH THE NATIONAL METEOROLOGICAL CENTER (NMC)

J. Derber
E. Kalnay*
M. Kanamitsu*
A. Leetma*
K. Miyakoda
D. Rodenhuis*
A. Rosati
W. Stern

* NMC

ACTIVITIES FY88

3.5.1 Collaboration with Development Section

A new phase in the NMC collaboration has begun with the new Section Chief, Dr. E. Kalnay. A discussion was held concerning the performance of summer cases in the MRF (Medium-Range Forecasts). This year, a technology transfer took place from NMC to GFDL in the following areas: the adjustment of SST for the Gibbs effect over the coastal ocean associated with the spectral representation of orography, lateral diffusion on pressure-surfaces as opposed to sigma-surfaces, and further development of the HIBU model.

3.5.2 Collaboration with the CAC (Climate Analysis Center)

Discussion has been initiated with regard to the technology transfer in the areas of global ocean modeling and the air-sea coupled model.

PLANS FY89

The transfer of the global ocean model to NMC will be started. Mesoscale data assimilation will be discussed jointly with the Development Section and also with CAC. The FGGE re-analysis efforts of GFDL and NMC will be evaluated and compared. Collaboration will be started on the subject of cloud-radiation interaction.

4. OCEANIC CIRCULATION

GOALS

* To develop a capability to predict the large-scale behavior of the World Ocean in response to changing atmospheric conditions through detailed, three-dimensional models of the World Ocean.

* To identify practical applications of oceanic models to man's marine activities by the development of a coastal ocean model which has a detailed surface layer and bottom boundary layer.

* To incorporate biological effects in a coupled carbon cycle/ocean GCM.

* To study the dynamical structure of the ocean through detailed analyses of tracer data.

4.1 OCEANIC-ATMOSPHERE INTERACTIONS

I. Held
G. Lau
M. J. Nath
D. Neelin
R. C. Pacanowski
S. G. H. Philander

ACTIVITIES FY88

The atmospheric GCM that was used to simulate the Southern Oscillation over a 15 year period (702) has been coupled with a tropical Pacific Ocean GCM that simulates El Nino realistically (681|. This coupled model has been used to simulate interactions between the ocean and atmosphere over a 28 year period. Even though the forcing, the annual mean incoming solar radiation, is steady, the coupled system has a broad spectrum of variability. It includes interannual oscillations that closely resemble the Southern Oscillation. In Fig. 4.1, which illustrates this variability, the low frequency fluctuations of different parameters are seen to be highly coherent, as is the case in reality. The spatial structure of the fields similarly agree with observations. For example, the sea surface temperature patterns in Fig. 4.2 closely resemble those observed during the peaks of the warm (El Nino) and cold phases, respectively, of the Southern Oscillation. The tongue of cold surface waters along the equator in the eastern half of the basin is well developed during the cold phase when the southeast tradewinds are intense, but is practically absent during El Nino when the warm surface waters surge eastward.

The mechanisms that sustain the continual irregular interannual oscillations include oceanic waves that are excited during one phase of the oscillation, whereafter they propagate westward before returning eastward as equatorial Kelvin waves to initiate the next phase of the oscillation. Not all warm events start in this manner, however, nor do all oceanic Kelvin waves lead to the next phase of the oscillation. Other mechanisms that also influence the oscillation are under investigation.

PLANS FY89

Analyses of data from the 28-year simulation are continuing in order to determine the processes that control fluctuations in different frequency ranges and to determine how fluctuations with different time-scales affect each other. At GFDL there are at least two more coupled models that simulate a realistic Southern Oscillation but these three model versions of this oscillation also have important differences when compared with each other and when compared with reality. The reasons for these differences will be investigated.

TEMPORAL VARIATION OF CIRCULATION INDICES FOR THE TROPICAL PACIFIC

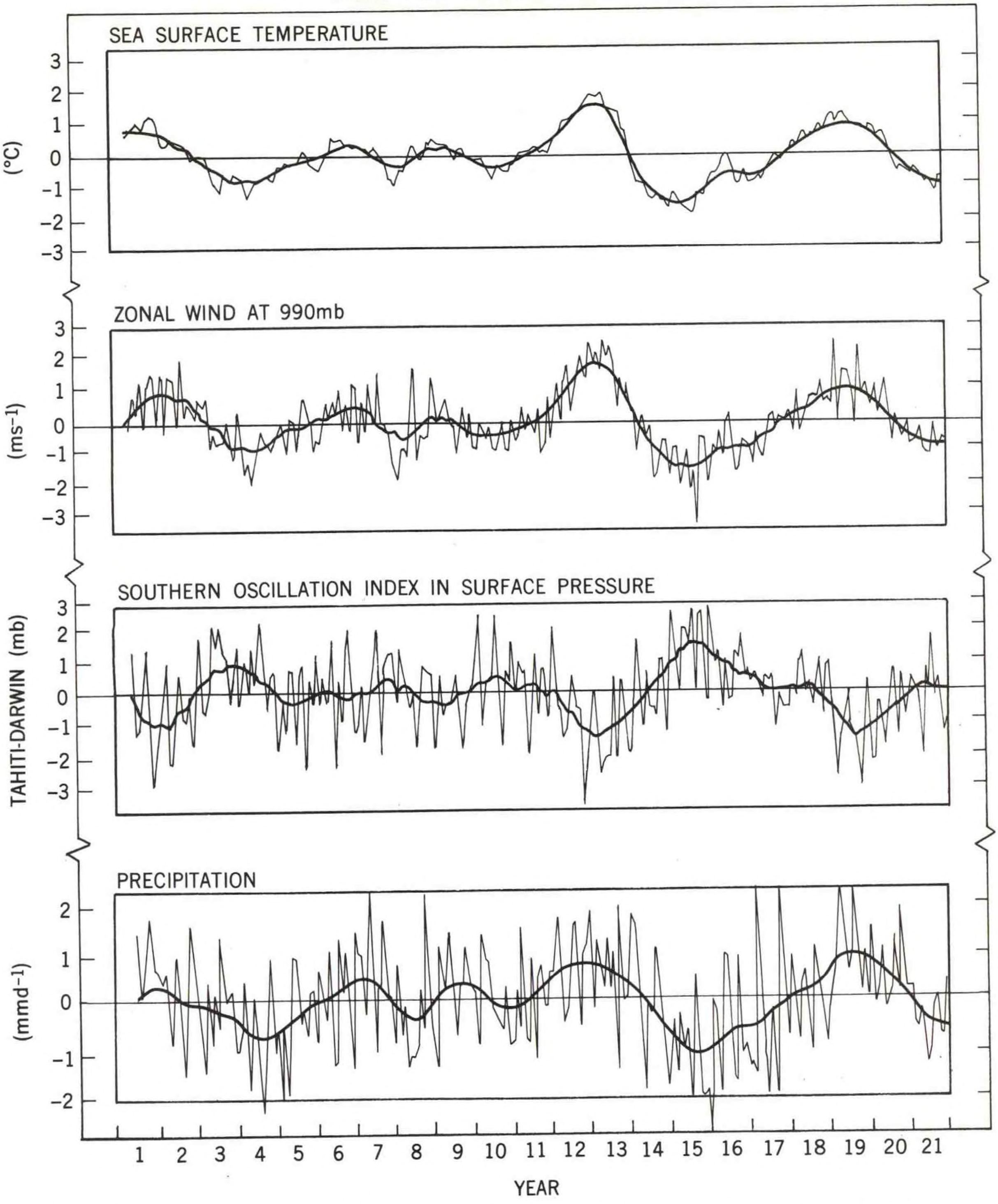

Fig. 4.1 Time series of monthly anomalies (thin curves) in sea surface temperature (SST), near surface zonal wind, the Southern Oscillation pressure index (SOI) and precipitation for the first 21 years of the coupled GCM experiment. The SST, zonal wind and precipitation indices are areal averages of model values over the equatorial central Pacific. The SOI is the difference between the surface pressures for the grid points corresponding to Tahiti and Darwin. The low-frequency signal (thick curves) represents the 13-month running means of the monthly data. Note that the SST anomalies tend to vary in phase with 990 mb surface westerlies and precipitation, and out of phase with the SOI.

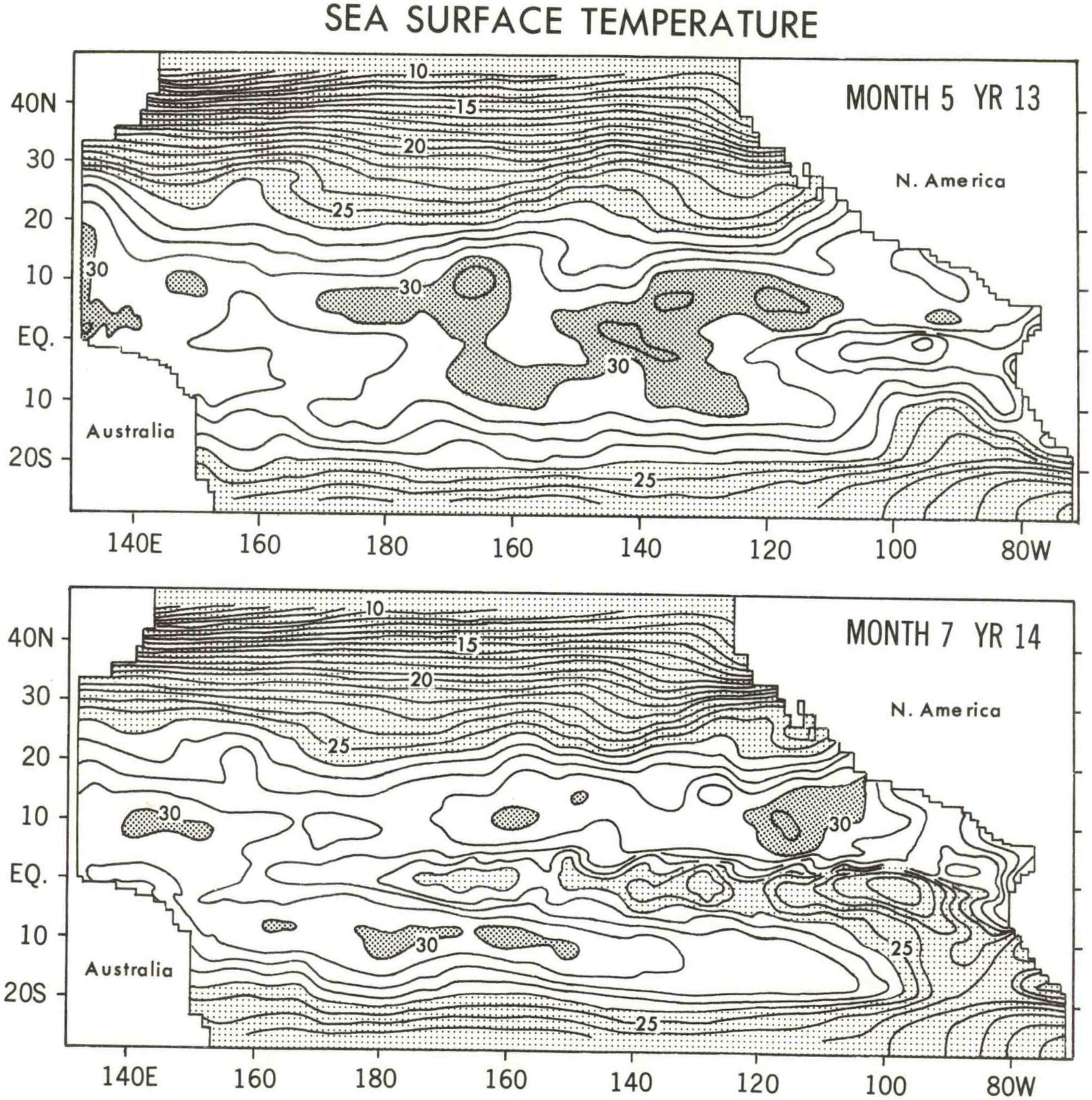

Fig. 4.2 The sea surface temperature (°C) at the peak of a warm event (month 5 of year 13) and at the peak of a cold event (month 7 of year 14). Note the pronounced cold equatorial tongue during the cold event and the appearance of waves, just north of the equator in the eastern part of the basin, because of instabilities of the mean oceanic currents. Shaded regions indicate temperatures greater than 30°C and less than 26°C.

4.2 OCEANIC RESPONSE STUDIES

P. Chang
W. J. Hurlin
R. Matano
R. C. Pacanowski
S. G. H. Philander

ACTIVITIES FY88

4.2.1 Oceanic Adjustment in the Presence of Mean Currents

The waves that effect the oceanic adjustment to a change in the winds are modified by the presence of mean currents, not primarily because of the shear of the currents, but because of the thermocline slope associated with the currents. Thus a westward current that causes the thermocline to shoal towards the equator can decelerate Rossby waves and slow down the adjustment (jo). Critical layers, where the waves are absorbed, can cause certain regions to be wave-free so that they remain unadjusted. A formalism has been developed to calculate the response of a shallow water model on an equatorial -plane to a given forcing function.

4.2.2 Simulation of Variability in Low Latitudes

In simulations of the seasonal cycle in the Atlantic Ocean the surface currents were found to be too intense, by a factor of two in some regions (767). It appeared that the parameterization of mixing processes is deficient. Calculations with improved mixing parameterization did not show a substantial improvement in the simulations. However, specification of more accurate surface heat flux conditions resulted in more realistic simulations. Apparently too large a heat flux into the ocean resulted in a very stable surface layer that inhibited vertical mixing.

The Equatorial Undercurrent in the model does not penetrate as far into the eastern part of the basin as it is observed to do. Analysis of model data indicate that in the east this current is an inertial jet that is retarded by horizontal mixing processes. A nonlinear horizontal mixing scheme was introduced into the model but thus far it has failed to improve the simulation.

PLANS FY89

Studies of the oceanic adjustment in the presence of mean currents with a realistic vertical structure are planned for 1989. (The calculations completed thus far assume that the waves and the currents have the same vertical structure but this is not so in reality.)

The General Circulation Models will be used to study the response of the deep ocean, below the thermocline, to the large seasonal changes in the upper ocean, and to examine how this response influences variations in the meridional heat transport.

4.3 MARINE GEOCHEMISTRY

L. Anderson	R. Murnane
T. Herbert	R. Rotter
R. Key	J. L. Sarmiento
N. Duprey Koehler	R. D. Slater
G. McDonald	R. Wong

ACTIVITIES FY88

4.3.1 Carbon Cycle Modeling

Carbon cycle models have advanced from studies in an idealized sector ocean model to a full, World Ocean configuration. The initial focus has been on the distribution of nutrients and oxygen in the interior of the ocean and the biological production of sinking organic particles in the upper ocean (872). The World Ocean configuration permits comparison between predicted nutrient and oxygen distributions directly with observed sections along ship tracks. Particle flux measurements can be compared directly with sediment trap observations.

Work proceeds on a sediment diagenesis model for $CaCO_3$ accumulation and dissolution which will couple the biogeochemical processes in the water column with transformations on the sea floor. Realistic simulation of the $CaCO_3$ feedback is necessary in order to integrate chemical cycle models for the long time periods appropriate to the study of the carbon cycle during the ice ages (ku, kt).

4.3.2 Transient Tracer Distributions

The central problem of how to make use of multiple transient tracer observations to infer ocean circulation and mixing rates, despite difficulty in reconstructing time rates of change and source functions, was studied. The results show that over much of the subtropical gyre, it seems to be possible to get reasonable estimates of the ventilation age from the tritium-helium-3 distribution, though the CFC-11 to CFC-12 ratio is not very useful due to the near constancy of this ratio in the atmosphere since 1975.

4.3.3 Models of Trace Metal Cycling

Two models are being used to study the cycling of strongly hydrolyzed metals (notably thorium) within the ocean. The first is a one-dimensional model of trace metal scavenging that follows the scheme used in three-dimensional carbon cycling models. This model can reproduce observed oceanic concentration profiles of dissolved and particulate thorium and protactinium. Inclusion of the routine in three-dimensional ocean models may give a better understanding of the causes of lateral variations in trace metal concentrations.

The second model assumes that the oceanic distribution of thorium isotopes can be described as a one-dimensional steady-state system with exchange of isotopes between dissolved, suspended particulate and sinking particulate phases. This scheme can use the steady-state concentrations from the above numerical model and predict the correct rate constants. Sampling strategies designed for this model require dissolved and filtered particulate samples as well as sediment trap data.

4.3.4 Ocean Tracers Laboratory

Work continued on the South Atlantic Ventilation Experiment (SAVE), a program to carry out data analysis and a radium-228 measurement program to improve our understanding of the patterns and rates of South Atlantic circulation, mixing and biological/chemical transformations. Progress was also made on the ARKTIS program, which is the attempt to collect chemical and physical oceanographic data from the Arctic Ocean.

PLANS FY89

The integration of the biological cycling formations into the three-dimensional ocean circulation models and incorporation of trace metal cycling models will continue to be a high priority. Field studies of tracer dynamics in the South Atlantic and Northeast Pacific will continue.

4.4 WORLD OCEAN STUDIES

K. Bryan
M. D. Cox
K. Dixon
B. Samuels
J. R. Toggweiler

ACTIVITIES FY88

The first phase of a detailed model evaluation study using Carbon-14 measurements has been completed (kn, kq). Carbon-14 is nearly an ideal tracer, because the natural Carbon-14 distribution can be used to study the long time scales associated with the abyssal circulation of the deep ocean, and the bomb-produced pulse of Carbon-14 introduced in the early 1960's can be used to study the shorter time scales of upper ocean ventilation. The downward pathways for substances introduced at the ocean surface are particularly important in connection with greenhouse climate projections. A key motivation is to develop models which will accurately predict the sequestering of atmospheric carbon dioxide and excess heat in the ocean.

Measurements of the NSF sponsored GEOSECS expedition show the main features of the uptake of bomb-produced Carbon-14 by the oceans as of one decade after the bomb tests. Measurements from coral reefs have recently supplied a new source of time-series data. Fig. 4.3 shows a comparison of model results and the coral measurements of Carbon-14. Note that sites in middle latitudes, such as Bermuda and Oahu, show a very rapid build up in the first decade after the tests and then an abrupt leveling off around 1970. Fanning Island, which is near the equator, has a much slower build up, which continues in the 1970's. The model simulates this difference between the subtropics and middle latitudes over wide areas in the Atlantic and Pacific. Analysis of the model reveals that equatorial upwelling initially moderates the build up of bomb-produced Carbon-14. As time goes on, the upwelling water, which largely originates in the subtropical thermocline, attains rather high values of Carbon-14. This explains why Carbon-14 values near equatorial water continues to rise after the Carbon-14 at Bermuda and Oahu have begun to decrease.

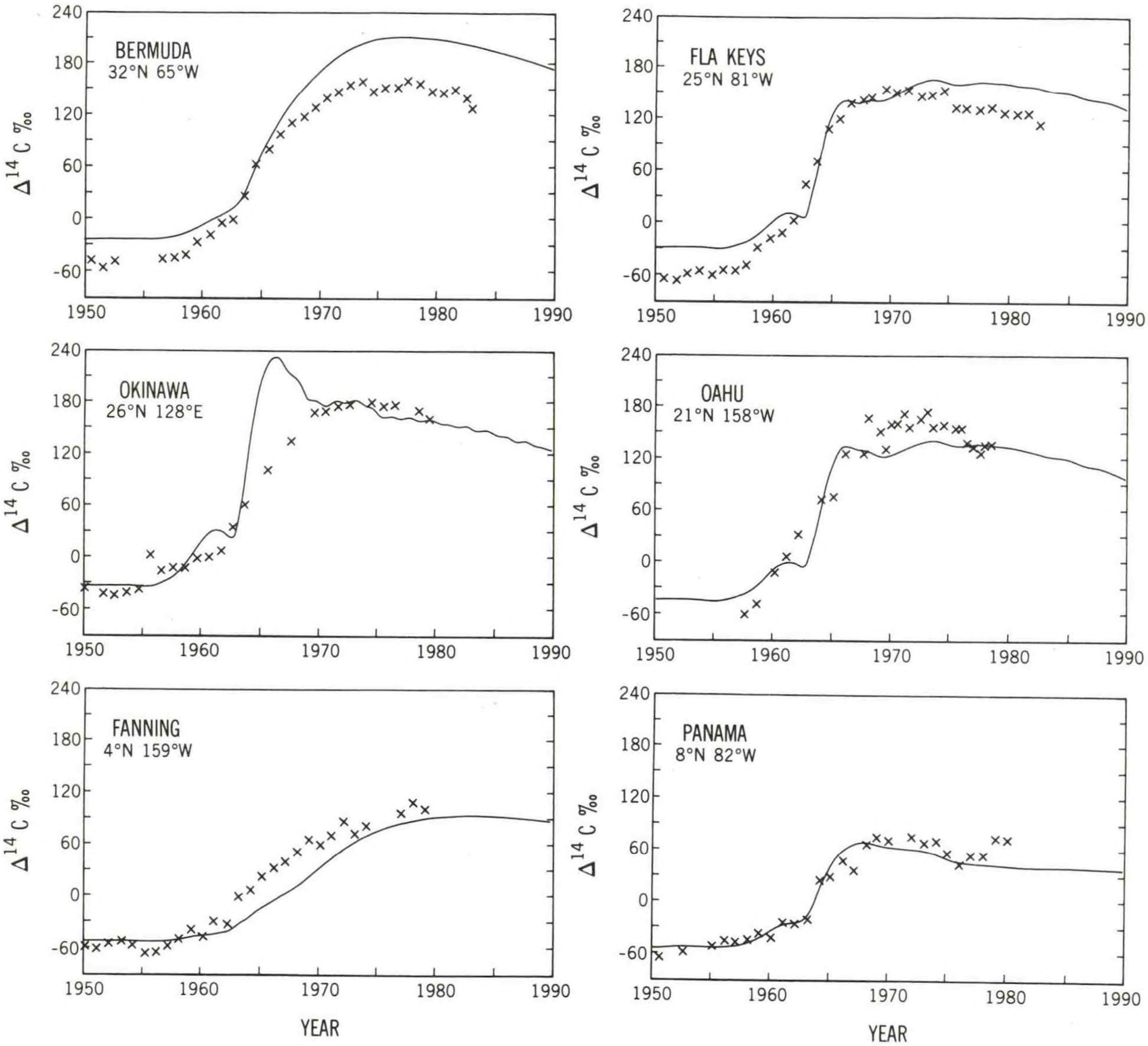

Fig. 4.3 The build up of surface values of Carbon-14 as a result of the bomb tests. The solid line is the value predicted by the model. Crosses are measurements taken from coral reefs. The ordinate is the ratio of Carbon-14 to Carbon-12 in parts per mil minus the pre-bomb test atmospheric value.

An important prediction of the model is that the character of the invasion of bomb-produced Carbon-14 changes in the decade after the GEOSECS measurements in the early 1970's. Input in middle and low latitudes nearly stops, while the main input shifts to the high latitudes of the Southern Hemisphere. The favored downward pathways for Carbon-14 in the model appear to correspond closely to regions that are believed to be main sites of Antarctic Intermediate Water formation. The region off the coast of Chile, just north of the Antarctic Circumpolar Current, is a major downward pathway in the model. Only a very small number of Carbon-14 measurements have been taken in recent years in the vicinity of the Drake Passage. However this limited data appears to be consistent with the model predictions.

PLANS FY89

In the coming year evaluation of the models using geochemical data will continue, using a new version of the model with increased vertical resolution and an improved parameterization of horizontal mixing. Simulation of both Carbon-14 and the CFC's will be undertaken. The CFC simulations will be carried out in cooperation with PMEL/NOAA staff who have collected an extensive observational data set in the Pacific Ocean.

4.5 OCEAN MODELING DEVELOPMENT

K. Bryan K. Dixon
M. D. Cox B. Samuels

ACTIVITIES FY88

Progress has been made in developing a hierarchy of models of the World Ocean with increasing resolution. All the models have a rather detailed (44 level) vertical resolution and include lateral mixing along isopycnals. Wind-forced convection in the mixed layer and vertical mixing inversely proportional to the Brunt-Väisälä frequency are also included. A simulation of the salinity structure of the North Atlantic is shown in Fig. 4.4. The model has a circulation in equilibrium response to seasonally varying, climatological data specified at the surface. The solution shown in Fig. 4.4(a) corresponds to the lowest horizontal resolution of the hierarchy (3.75° of longitude and 4.5° of latitude). Also shown are the observations of salinity for the same section and another model which is identical except with only twelve layers instead of 44 layers in the vertical. Compared with previous simulations the new model shows a significant increase in the accuracy of simulating the main thermocline and important water mass features such as the Antarctic Intermediate Water. The intensity of the overturning circulation in the Atlantic in the simulation is also much closer to observational estimates.

PLANS FY89

Sensitivity tests will be carried out to determine which improvements to the model are most important for simulating water mass properties. Special efforts will be made to improve the efficiency of the model in simulations of water mass properties and for tracer studies.

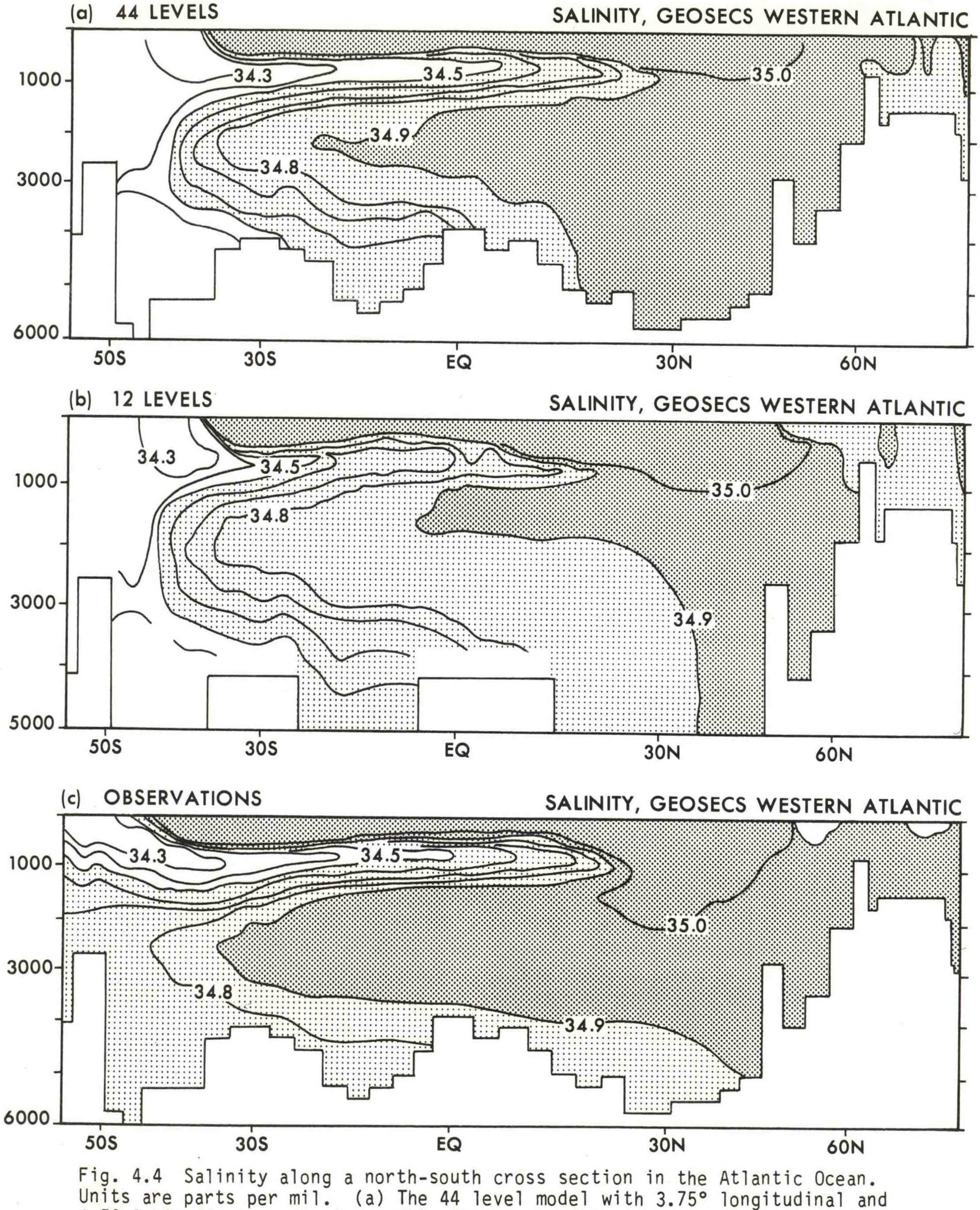

Fig. 4.4 Salinity along a north-south cross section in the Atlantic Ocean. Units are parts per mil. (a) The 44 level model with 3.75° longitudinal and 4.5° latitudinal resolution. (b) The same model with only 12 levels in the vertical. (c) Mean observations from (528).

4.6 COASTAL AND ESTUARINE OCEANOGRAPHY

B. Galperin   L.-Y. Oey
G. L. Mellor   H. J. Xue
L. Kantha

ACTIVITIES FY88

4.6.1 Delaware Bay and River

Analyses of the Delaware Bay and River simulations and comparisons with the NOS 1984 observations have been completed. The calculations compared quite well with observational surface elevations, currents and salinities. The model is capable of hindcasting the salinity intrusion during the drought of the Fall of 1984.

4.6.2 Gulf Stream Model Development

A regional model of the Gulf Stream has been constructed. In the vertical, it has sigma coordinates which conform to the bottom topography whereas in the horizontal it uses orthogonal, curvilinear coordinates which conform to the United States Atlantic Seaboard as shown in Fig. 4.5. Otherwise, the model is approximately bounded in the south by 27°N and in the east by 64°W. The grid resolution varies but is about 20 km on the average. As seen in Fig. 4.6, Gulf Stream separation at Cape Hatteras is obtained as are meanders and eddies. The eddies do not yet appear to break off into realistic cold core or warm core rings with long lifetimes. The intrusion flow is sensitive to the eastern boundary conditions and the stream separation is directly related to the strong, nearly barotropic, southwestward slope current.

PLANS FY89

Model development will continue to more completely delineate separation dynamics for the Gulf Stream. This project is sponsored by the Institute for Naval Oceanography; to meet their goals, we will begin to assimilate data into the model using GEOSAT altimetry data and the relatively dense XBT and AXBT available in this part of the ocean.

4.7 COUPLED ICE-OCEAN MODELS

S. Hakkinen   G. L. Mellor
L. H. Kantha

ACTIVITIES FY88

A one-dimensional ocean model incorporating second moment turbulence closure has been constructed and coupled to an ice model. Attention has been given to the molecular sublayer separating the ice and the oceanic turbulent surface layer. The ice model accounts for ice divergence and ice concentration. Several empirical coefficients related to the thermodynamics of open leads and to the distribution of ice thickness have been defined, estimated and evaluated as to their sensitivity to annual mean thickness in the central Arctic Ocean (kc).

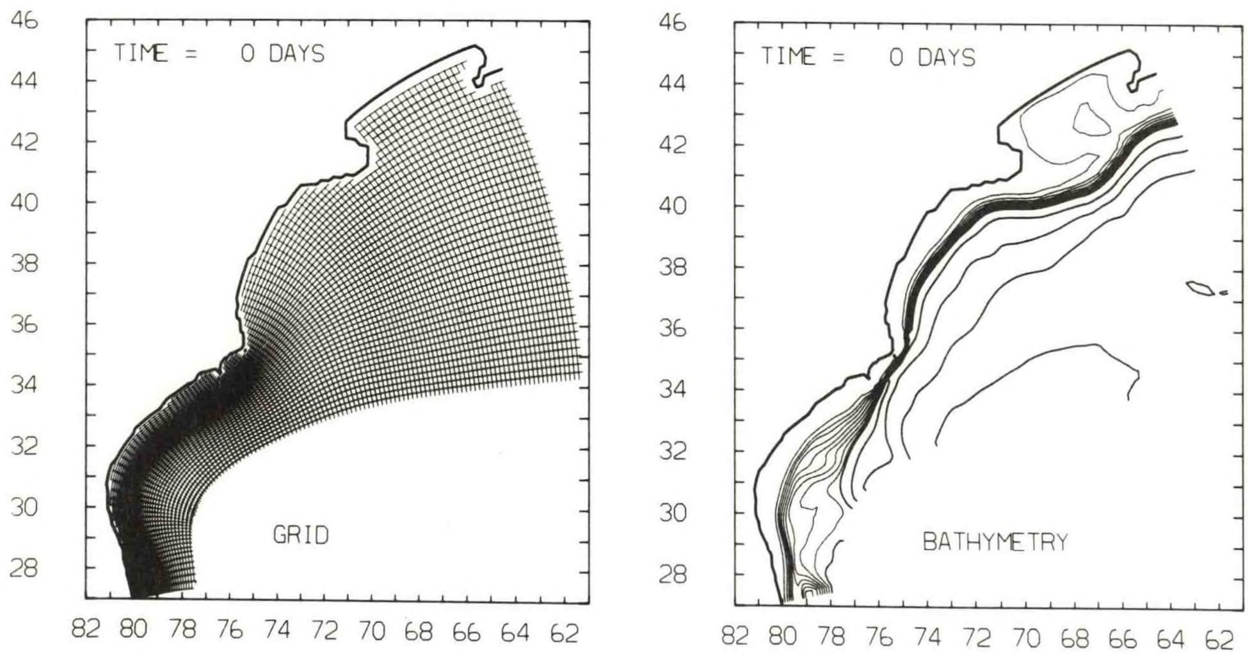

Fig. 4.5 An orthogonal, curvilinear grid applied to the western part of the North Atlantic. The left panel is the grid whereas the right panel is the bathemetry (light lines are 100m isobaths, boundary lines are 1000m isobaths.)

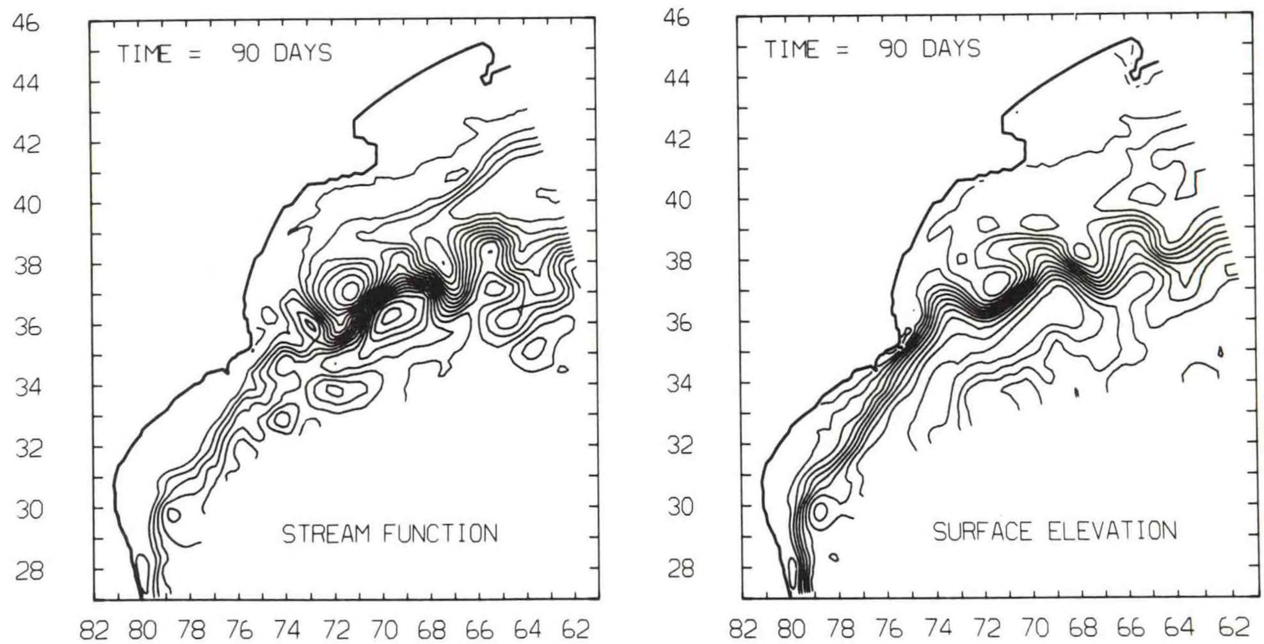

Fig. 4.6 A result from an exploratory run of the model, 90 days after initialization with temperature and salinity climatologies.

The same model, now expanded to two-dimensions (in the vertical plane) has been applied to the marginal ice zone in the Bering Sea. The model produces realistic frontal structures when compared to observations (kd).

The two-dimensional, coupled ice-ocean model has also been applied to the marginal ice zone with surface forcing consisting of strong upwelling, favorable winds (12 m s^{-1}) and strong surface heat loss (f600 Wm^{-2}). The model shows that convection will occur in nine days down to 1 km in a water column resembling Greenland Sea conditions near the ice edge. As an intermediate step, when convection penetrates down to the bottom, the model shows several convection cells with scales of about 1 Rossby radius of deformation or about 4 km; the events last for about two days.

PLANS FY89

The Greenland Sea simulation will be extended to 3-dimensions to study deep water formation and dissipation of convective cells.

A model encompassing the Arctic Ocean and the Greenland-Iceland-Norwegian Seas will be constructed. Aside from the challenge of creating a model capable of realistic simulations and subsequently useful for climate studies and nowcasts/forecasts, several questions can be answered, examples of which are: Where does the Atlantic water cooled in the Barents Sea go? Is ice production on the shelves responsible for the Arctic deep water production?

4.8 SECOND-ORDER TURBULENCE CLOSURE MODELING

B. Galperin G. Mellor
L. Kantha A. Rosati

ACTIVITIES FY88

A second-order turbulence closure model similar to the level 2-½ model of Mellor and Yamada has been applied to rotating stratified flows. Along with in-depth investigation of the combined effect of rotation and stratification, the study concentrated on the Garwood hypothesis that the poleward component of the Coriolis parameter is responsible for the observed disparity in the mixed layer depths in the east and west regions of the equatorial Pacific Ocean. Results of this study are described in (jf, jt, kj). One of the general conclusions of the study is that stable stratification limits the value of the turbulence length scale which in turn suppresses the rotation effect.

5. PLANETARY CIRCULATIONS

GOALS

* To understand the fundamental dynamical processes influencing global circulations.

* To develop numerical models capable of simulating planetary-scale processes in a planetary context.

5.1 PLANETARY CIRCULATIONS

G. P. Williams J. Wilson

ACTIVITIES FY88

5.1.1 Global Circulations

Circulation dynamics has been studied by altering the strength, size, and mix of the jets, cells, and eddies by varying the rotation rate and, hence, the Rossby and Froude numbers of moist, dry, surface-slip, axisymmetric, oblique, and diurnal atmospheric GCMs. Such changes allow us to isolate the circulation invariants. Circulation variability was thus found to be limited to the mix of a few elementary components, (Fig. 5.1), with a natural-Hadley (NH) element and a tropical quasi-Hadley (QH) element prevailing at low and high rotation, and with a momentum-traversing (QG_γ) element and momentum-converging (QG_β) element occurring in baroclinically unstable midlatitudes at medium and high rotation. Standard circulation theory works well in explaining the various states, but a dynamical isomorphism between the symmetric-Hadley (SH) and β-turbulence theories for the mean flows and the eddies, suggests that a more fundamental, more unified way may exist for describing global circulations (see (864, gq)).

Moist circulations vary from the single polar jet of the NH element at low rotation, to the hybrid jet of the overlapping (QG_γ + QH) elements at medium rotation, to the ($QG_\gamma + QG_\beta$ + QH) jets at high rotation. Dry circulations have a similar progression but blocking easterlies replace the QH element in low latitudes. Surface-slip systems also lack a Hadley mode and develop a strong barotropic component and tropical easterly jet. Dry circulations can develop a tropical westerly jet only if a localized surface heating exists that imitates latent heating near the equator. Axisymmetric circulations vary from a single jet at medium rotation to double jets at high rotation, together with two pairs of Hadley and Ferrel cells, and appear to be more inviscid, more nonlinear, and of higher-order than in standard SH theory. Solstitial circulations contain an easterly jet in the summer subtropics that forms a QG-Hadley (QGH) element governed by both quasi-geostrophic (QG) and Hadley dynamics. The nonlinear baroclinic instability and wave dispersion in the QGH easterly jet lead to a vertically bimodal $\overline{v'M'}$ zonal momentum flux, (Fig. 5.2). Diurnal heating plays a fundamental role at low rotation by strongly boosting the momentum-transporting planetary waves and their equatorward $\overline{v'M'}$ flux to change the narrow polar NH jets into broad midlatitude westerlies during the asymptotic, diurnal, and Halley transitions that occur as rotation approaches zero.

5.1.2 Planetary Vortices

Numerical studies of the stability and genesis of Rossby vortices in the single layer system were completed (851). These vortices provide a simple prototype of geostrophic coherence and of Jupiter's Great Red Spot and Ovals. Vortex behavior was found to be dependent on spherical location and on balances among the translation, twisting, steepening, dispersion and advection processes. Advection is the main stabilizer and tends to restore radial symmetry, while twisting is the main destroyer and tends to break radial symmetry; both processes prevent a simple Korteweg-deVries dynamics.

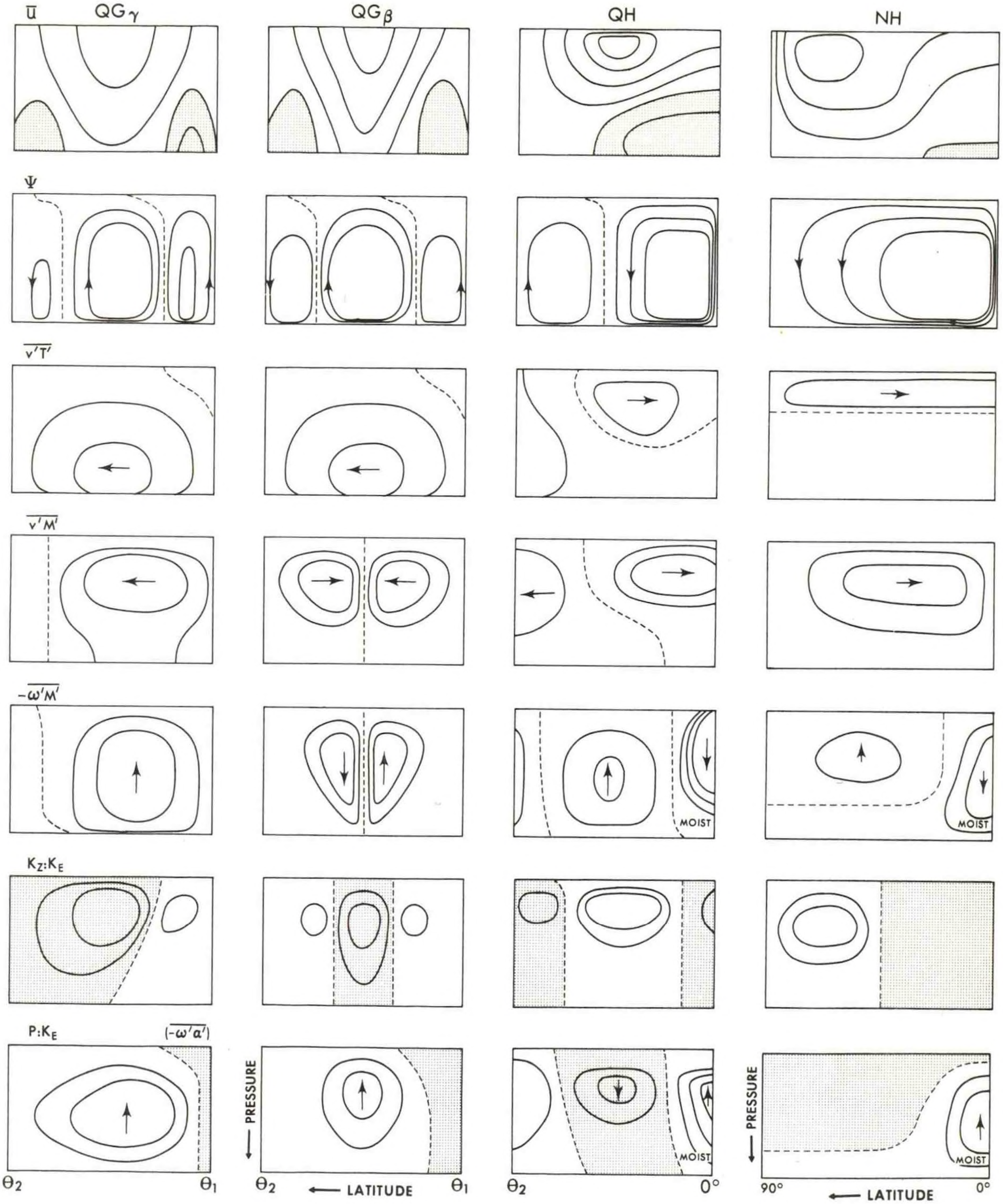

Fig. 5.1 Schematic summary of the quasi-geostrophic (QG_γ and QC_β), quasi-Hadley (QH), and natural-Hadley (NH) equinoctial circulation elements in terms of their mean flows, eddy fluxes, and energy conversions.

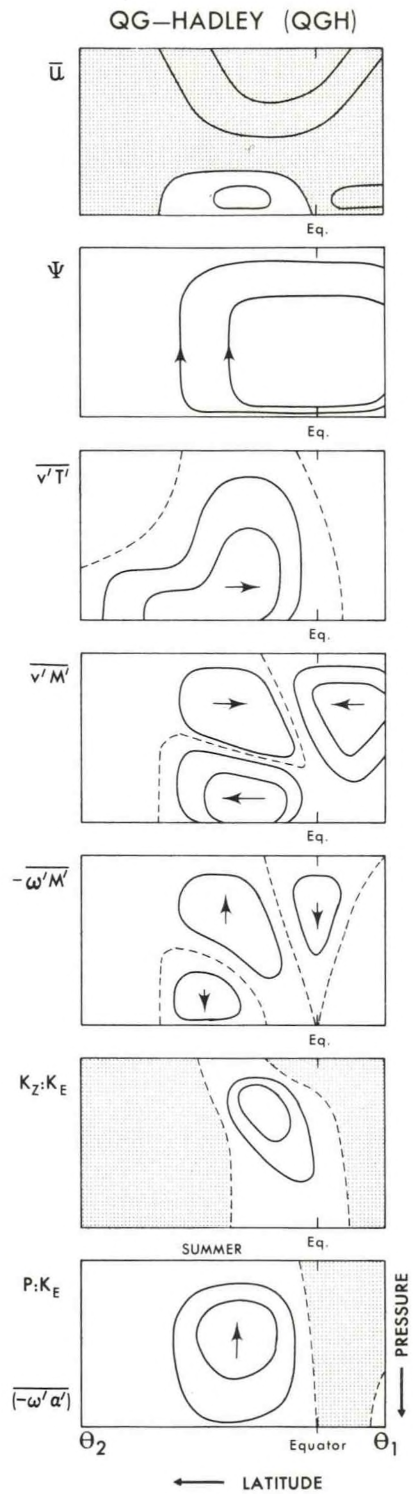

Fig. 5.2 Schematic summary of the quasi-geostrophic-Hadley (QGH) circulation element that occurs in low summer latitudes during solstice at medium and high rotation.

Stable anticyclones exist at all latitudes but under constraints that vary from midlatitudes to low latitudes to the equator. In midlatitudes, stable anticyclones exist in a variety of sizes and balances and merge during encounters. In low latitudes, stable anticyclones exist only when a strong equatorial westerly jet and subtropical easterly jet are present to limit the highly-dispersive equatorial modes. At the equator, stable anticyclones exist only when they have a special Hermite latitudinal form and a Korteweg-deVries longitudinal form; they act like solitons among themselves but tend to reduce low latitude vortices. Vortices can be generated by shear instability or by eddy forcing. The vortex number depends on nonlinear interaction history more than on linear instability factors: vortex merging, not the vorticity source, determines the vortex state. Wave-packet perturbations of unstable shear zones or forced eddies both develop into unequal vortices that merge into a single vortex in a broad zone or into a double vortex in a narrow zone.

To extend vortex theory to continuously stratified systems, a three-dimensional channel model was developed with a high-resolution, a fast Poisson solver, and a weakly dissipative differencing scheme. Preliminary calculations were made to check the model and the new initialization procedures.

PLANS FY89

The three-dimensional vortex model will be further developed, along with the necessary theory and analysis procedures, to examine when anticyclones are stable in continuously stratified atmospheres and how they may be generated. A new circulation model will be designed for examining the role of various physical factors in controlling the various planetary circulations.

6. OBSERVATIONAL STUDIES

GOALS

* To determine and evaluate the physical processes by which the atmospheric and oceanic circulations are maintained, using all available observations.

* To compare results of observational studies with similar diagnostic studies of model atmospheres and model oceans developed at GFDL and thereby develop a feedback to enhance understanding in both areas.

6.1 CLIMATE OF THE ATMOSPHERE

Y. Kushnir
A. K. Lau
N. C. Lau
N. Nakamura
M. J. Nath
A. H. Oort
J. P. Peixoto*
M. Rosenstein
H. Savijarvi*

* University of Lisbon, Portugal

ACTIVITIES FY88

6.1.1 Data Processing

Raw global rawinsonde data from NMC (provided by R. Jenne at NCAR) for the period May 1973-December 1987 have been unpacked, thus providing the basis for the extension of the GFDL global upper air data base to a full thirty-year set extending from May 1958 to April 1988. Eight years of the new 15-year data set have been thoroughly error-checked and analyzed on a 1.5° latitude x 2° longitude grid. Preliminary results for the hemispheric mean temperatures show a similar 6-month lag with the sea surface temperature anomalies in the eastern Equatorial Pacific Ocean (an ENSO indicator) as was found earlier for the Northern Hemisphere only (556).

An extensive data set consisting of daily or twice-daily grid point NMC analyses of the geopotential height, temperature and wind fields at all available tropospheric and lower stratospheric levels for the 1946-84 period has recently been acquired from the University of Washington. This comprehensive archive will serve as a valuable data base for diagnostic studies of atmospheric variability on a wide range of time scales.

6.1.2 Angular Momentum, Water and Energy Budgets

Atmospheric budgets of the kinetic energy, sensible heat, latent heat and total energy have been computed for the FGGE year over North America and the North Atlantic using the ECMWF analyses. Similar calculations are also presented for the 1963-1973 period over Mexico and the Gulf of Mexico using the GFDL data. The results indicate increased low-level dissipation over the mountainous areas and upper-level acceleration, thus suggesting subgrid-scale energy transfer to synoptic scales possibly associated with frontal circulations or mesoscale cumulus convection (868).

Reasonable geographical patterns of the vertically integrated budgets of moisture and energy have been obtained by the use of the vorticity equation to evaluate the mean divergent component of the wind in midlatitudes (856). This method seems to overcome some of the notorious difficulties in obtaining the contributions of the divergent wind component to regional budgets.

Estimates were made of the interannual variability in the energy budgets of the Arctic and Antarctic polar caps poleward of 70° latitude. These estimates make it possible to calculate probable error estimates of the various terms in the budgets (ig). The analyses were also extended to include the water budget leading to tentative order of magnitude estimates of the water-ice budgets in the polar regions.

The preparation of a comprehensive publication summarizing our present knowledge of the climate system is nearing completion. Many of the basic chapters have been reviewed and extensive revisions are being made accordingly. New analyses and discussions of the radiation balance, the cryosphere and the entropy budget have been added. The entropy budget provides fresh insights since it shows the direction in which the atmospheric processes tend to proceed rather than being only a diagnostic tool.

6.1.3 Structure and Evolution of the Asiatic Summer Monsoon

The three-dimensional structure and seasonal evolution of the summer monsoon over South and East Asia have been examined using an 8-year observational data set produced by the ECMWF. Particular attention has been focussed on the migration of the climatological convective heating center and its impact on various monsoonal features as the summer season advances. The preferred propagation path and temporal characteristics of synoptic transient disturbances in the monsoon region were also analyzed. It was noted that the behavior of such large-scale circulation features as the subtropical jet stream, monsoon trough, West Pacific subtropical high pressure center in the middle and low troposphere, and the Tibetan high pressure zone near the tropopause are all closely linked to the distribution of heat sources and sinks. Interesting wave-like disturbances with periods of several days have also been detected over the South China Sea and Bay of Bengal during the July-August period.

6.1.4 Dynamical Interactions Between Transient Fluctuations of Various Time Scales

The principal modes of month-to-month variability of the midlatitude storm tracks, as reported in recent studies based on shorter data records (jn,jd), have all been reproduced in the more extended (1946-1984) NMC data set. Further analyses have revealed that such storm track modes are significantly correlated with zonal wind anomalies associated with variability of the flow pattern on interannual time scales, thus inferring strong dynamical interactions between the synoptic disturbances and the quasi-stationary flow. Fluctuations of the storm tracks were also seen to be accompanied by notable changes in sea surface temperature over the midlatitude oceans. A comprehensive understanding of midlatitude large-scale air-sea interaction must therefore take into account the dynamics of the storm tracks.

A global analysis has shown that the budgets of the day-to-day variances of potential temperature and specific humidity (θ'^2, q'^2) are maintained largely by the down gradient heat and moisture transport by transient eddies in the midlatitude baroclinic zones. In contrast, the budgets of the mean squared potential temperature and specific humidity (θ^2, q^2) appear to be governed by the time-mean sources (850, ih).

PLANS FY89

The data reduction and objective analysis of the monthly upper air anomaly fields for the 15-year period May 1973-April 1988 will be completed. Possible reanalysis of the Southern Hemisphere fields will be investigated and tested using the more complete Australian data archives (831).

Extensive updates of the sections on "Long-Period Fluctuations" and "Mathematical Simulation of Climate" as well as final revisions to the other chapters should complete the preparation of our publication on the Physics of Climate.

The temporal and spatial behavior of the synoptic-scale transient fluctuations observed in the monsoon region will be documented in detail using both ECMWF analyses and satellite observations of the outgoing longwave radiation. The relationships between these disturbances and the quasi-stationary monsoon flow will be explored.

The nature of the interactions between the baroclinic cyclones and the low-frequency component of the extratropical circulation will be investigated by examining the behavior of eddy vorticity and heat fluxes associated with the storm track modes and the effects of such eddy forcing on the time-mean state.

6.2 AIR-SEA INTERACTIONS

M. Jackson
N.-C. Lau
S. Levitus
M. J. Nath
A. H. Oort
Y.-H. Pan
M. Rosenstein

ACTIVITIES FY88

6.2.1 Data Processing and Preparation of a Long-Term Climatology

Climatological monthly estimates of the means and variances of various surface marine parameters, such as the sea surface temperature, air temperature, wind components, relative humidity and cloudiness, have been completed and will be published as an atlas. These estimates are based on the entire COADS record from 1870 through 1979.

Monthly analyses of the most important COADS parameters were completed for the 1950-1979 period both in terms of the 30-year means as well as for the anomalies from the 30-year mean. When updated to 1988 in the near future, this set combined with the upper air data in 6.1.1 will provide a unique picture of the combined atmosphere-earth surface system and its year-to-year variations during the 1958-1988 period. The uniqueness stems from the length of record and the uniformity of the basic data sets, and of the data reduction and analysis systems used.

6.2.2 Correlation Analyses of the SST Anomalies

SST anomalies in the Eastern Equatorial Pacific (EEP) are well correlated with SST anomalies in the tropical and world ocean at intermonthly and interannual time scales. SST anomalies in the Indian and Atlantic oceans are found to lag behind those in the EEP region by about one to three months, respectively. On the interannual time scale, the EEP anomalies show a correlation of +0.8 with the tropical ocean and of +0.6 to +0.7 with the world ocean anomalies (kf).

6.2.3 Response of the Atmospheric Circulation to Extratropical SST Anomalies

Intensive diagnosis has been performed on a 35-year GCM experiment in which month-to-month changes of the observed SST over the World Oceans were incorporated in the lower boundary condition. It was revealed that the principal modes of midlatitude wintertime variability of the model atmosphere are most strongly correlated with SST anomalies at two maritime sites in the extratropics. One of these sites is located near Newfoundland and the other is situated north of the Hawaiian Islands (jg). Such model results are consistent with recent observational findings based on historical archives for the recent decades. The SST anomalies at these two centers of action are associated with significant perturbations in both the simulated seasonally averaged flow, as well as with the location and intensity of the oceanic storm tracks. The precipitation signals accompanying such midlatitude SST changes appear to be largely determined by displacements in the storm track axes. The results from this GCM simulation reinforce the notion (see section 6.1.4) that storm track dynamics provides an important component of large-scale air-sea interaction in the extratropics.

6.2.4 Diagnosis of Coupled Ocean-Atmosphere GCMs

The atmospheric model output from a 28-year fine-mesh coupled ocean-atmosphere GCM experiment (see section 4.1) has been processed and various key indices of the El Nino-Southern Oscillation (ENSO) phenomenon have been constructed (jg). The time series of these circulation indices as well as synoptic maps of selected atmospheric variables indicate that the tropical model atmosphere undergoes notable changes in association with the ENSO cycles mentioned in the coupled system (see Fig. 4.1). The amplitudes of, and phase relationships among, different indices are in good agreement with their observational counterparts.

Through the cooperation of the Climate Dynamics Project, the model output from a 120-year experiment with a crude-resolution coupled ocean-atmosphere GCM (see section 1.2.2) was made available for ENSO diagnosis. The tropical Pacific basin of this model was seen to exhibit quasi-regular oscillations with 2-3 year time scales (Fig. 6.1). Such interannual variations are accompanied by oceanic and atmospheric signals which are reminiscent of the observed ENSO features (jg). Since this crude-resolution model and the fine-mesh model described in the preceding paragraph tend to emphasize different sets of dynamical processes, a detailed comparison between the results from these two experiments should delineate the essential mechanisms responsible for the simulated ENSO events.

PLANS FY89

Investigations of the structure of the year-to-year anomalies at the ocean surface will continue. They will be combined with similar investigations of the upper air (6.1.1) and the radiation budget terms as observed by satellites. The latter work will be done in cooperation with Professor T. Vonder Haar and collaborators at Colorado State University. These projects will enable us to obtain a more integrated picture of the behavior of the climate system during the past 30 years.

The physical and dynamical processes responsible for the sensitivity of the storm tracks to midlatitude SST anomalies will be further investigated.

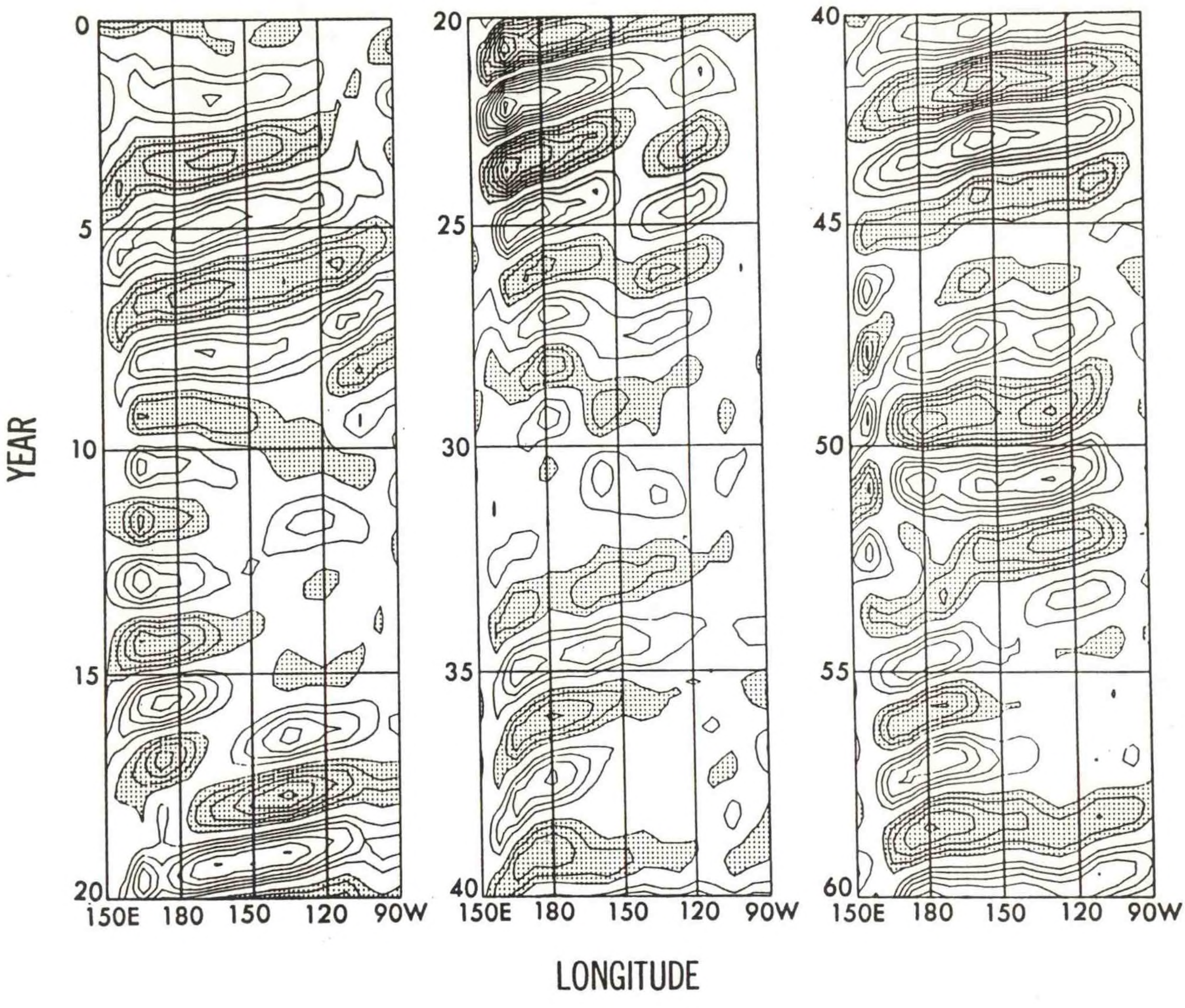

Fig. 6.1 Longitude-time distribution of the band pass (24-51 month) filtered SST anomaly between 2.25°S and 2.25°N for a 60-year segment of the crude-radiational coupled GCM. Contour interval: 0.1°C. Stippling indicates values less than 0.1°C. The zero contour is omitted for the sake of clarity. Note the tendency for SST anomalies to migrate westward with time.

The extent to which the time-mean response of the model atmosphere may be attributed to transient eddy forcing will be assessed.

In view of the irregularity of the ENSO cycles in the fine-mesh model, the synoptic behavior of the coupled system during each of the anomalous events will be examined in greater detail, so as to document the multiple causes of ENSO phenomena appearing in that experiment. The regularity of the ENSO episodes in the crude-mesh model suggests that composite analysis might be a fruitful approach for examining the relevant processes.

6.3 CLIMATE OF THE OCEAN

S. Ascher   S. Levitus
M. Jackson   A. H. Oort

ACTIVITIES FY88

6.3.1 Data Processing

The National Oceanographic Data Center (NODC) files containing mechanical bathythermograph data, expendible bathythermograph data, and hydrographic data through mid-1988 are being processed. Quality control techniques previously developed (jq) are being applied to these data. These new data will be used in the study of temporal variability of the thermohaline structure of parts of the World Ocean.

6.3.2 Annual Cycle in the Upper Ocean

Studies of the annual cycle of meridional Ekman heat and volume fluxes in the world ocean have been published (832, 857). The Indian Ocean is found to be responsible for a significant fraction of the total meridional fluxes of heat and mass on the annual mean time scale. The annual cycle of mixed-layer depth, steric sea level, and of surface currents based on ship drift data are being examined.

6.3.3 Long-term Variations in the Thermohaline Structure of the Ocean

A first study of temporal variability of the thermohaline structure of the North Atlantic Ocean is near completion. Between the 1955-59 and 1970-74 pentads the subtropical gyre of the North Atlantic Ocean exhibited a cooling at standard depth levels as indicated in Fig. 6.2a. These changes were due to the upward displacement of potential density surfaces (Fig. 6.2b) which generally showed only small changes in potential temperature (<0.25°) between pentads (Fig. 6.2c). The 26.5 potential density surface exhibited the greatest vertical displacement of any density surface in the subtropics. This surface is associated with the convectively formed Subtropical Mode Water. The upward displacement of this surface coupled with an observed increase in potential vorticity between pentads (for surfaces above the 26.5 surface) indicates that convection weakened and in fact may not have occurred during all or part of the 1970-74 pentad as compared to the 1955-59 period.

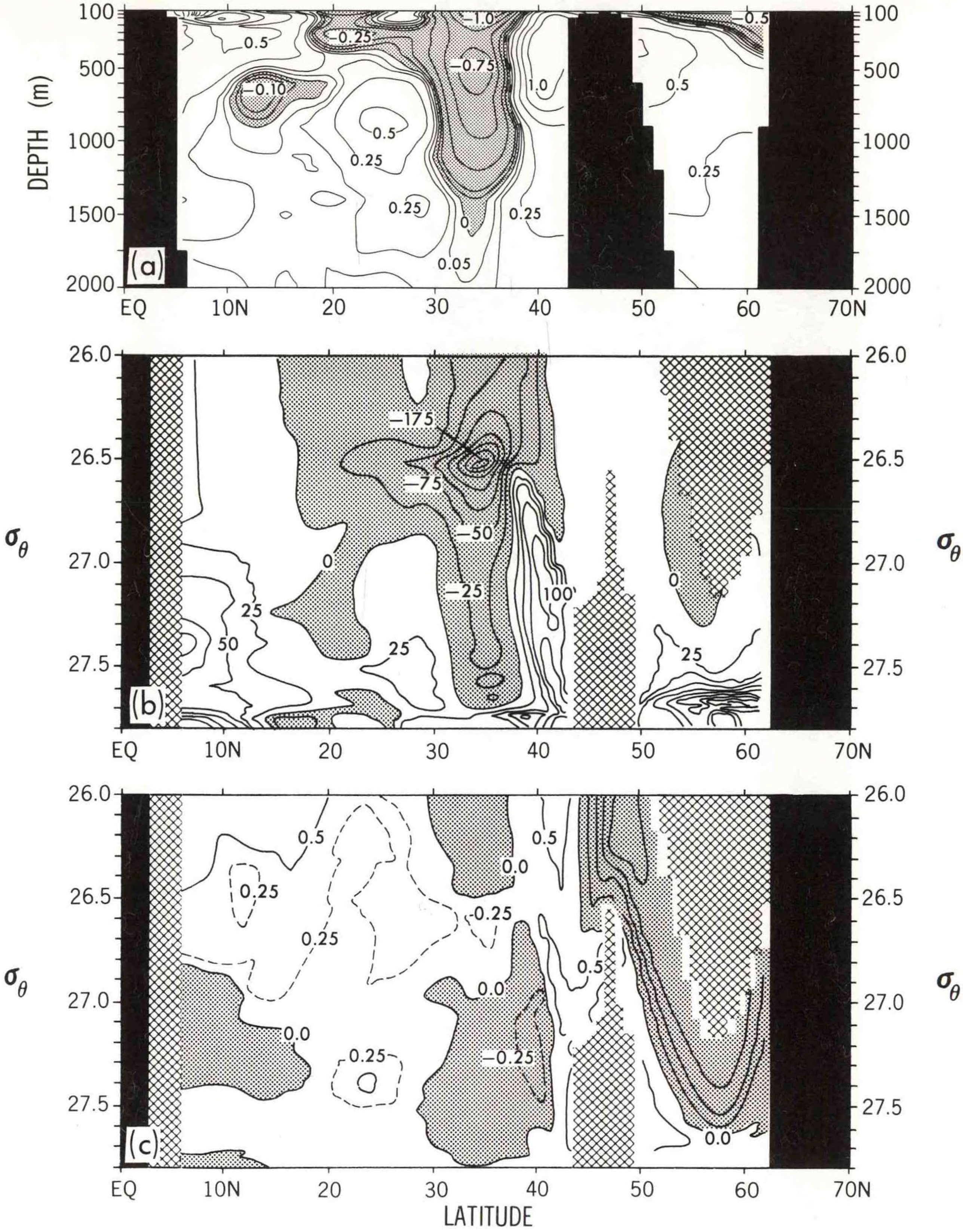

Fig. 6.2 Distributions along 49.5°W for 1970-74 minus 1955-59 of a) Temperature difference (°C) versus depth; b) Depth difference (m) of potential density surfaces; and c) Potential temperature differences on potential density surfaces.

6.3.4 Ocean Energetics

The earlier estimates of the available gravitational potential energy (APE) in the world oceans have been modified using a more accurate expression for the static stability in the ocean. The new values show that the APE in the ocean between the surface and 1000 m depth is a factor of 10 smaller than the APE in the atmosphere. The kinetic energy ratio is even smaller, i.e., on the order of 1/200. These estimates are in sharp contrast to the ocean-atmosphere ratio of more than 1000 for the total internal plus potential energy (jz).

PLANS FY89

Quality control and analysis of all the NODC hydrographic, XBT, and MBT data files (updated through 1988) will begin. These new data will be used for further studies of ocean variability in the post 1945 period. The geographical distribution of oceanographic data gathered before World War II (jr) is not favorable for studies of interannual variability.

Further studies of the annual cycle of various parameters characterizing the state and motion of the upper ocean will continue.

7. HURRICANE DYNAMICS

GOALS

* To understand the genesis, development and decay of tropical disturbances by investigating the thermo-hydrodynamical processes using numerical simulation models.

* To study small-scale features of hurricane systems, such as the collective role of deep convection, the exchange of physical quantities at the lower boundary and the formation of organized spiral bands.

* To investigate the capability of numerical models in the prediction of hurricane movement and intensity.

7.1 GENESIS OF TROPICAL CYCLONES

Y. Kurihara R. E. Tuleya

ACTIVITIES FY88

7.1.1 Genesis Mechanism

Vorticity budget analysis was made with respect to two numerical integrations of easterly waves performed in the previous year. It was found that, in the case of a developed storm (Hurricane David, 1979), combination of vorticity stretching and non-linear relative advection of relative vorticity caused an increase of cyclonic vorticity in the deep layer above the disturbance center. Whereas in the case of the non-developing wave, positive tendency due to stretching was not deep and the effect of relative advection was not positive at the disturbance center.

Starting from a weak disturbance, which developed later into Hurricane David in a control simulation experiment, two integrations were carried out, the one with uniform evaporation of climatological value (.4 cm d^{-1}) at all times and the other without evaporation. The sensible heat flux in both integrations was computed by the same scheme with the control experiment. The obtained results clearly suggest that the latent heat flux is certainly needed but the evaporation-vortex feedback is not necessarily required for an incipient tropical wave to develop to a disturbance with the strength of a tropical storm. Compared to the control simulation of David, the central pressure of the developed storm with constant latent heat flux was shallow and the wind and temperature fields in it exhibited somewhat disorganized structure. It is speculated that the evaporation-vortex feedback mechanism probably works to produce a deeper compact vortex.

7.1.2 Genesis of Real Tropical Storms

Tropical cyclogenesis takes place in an environment which generally possesses regional features. Hurricane Hazel, 1979, developed from a weak system off the northwest coast of the dry land of Australia. Numerical experiments with a $\frac{1}{4}$° resolution regional model are in progress to simulate the evolution of Hazel. Numerical results obtained so far suggest that the orographic effect is an important factor for the formation of this storm. The model with the Navy high resolution mountains was capable of treating the above effect but that with the truncated mountains of the R30 spectral model was not. The experiments also demonstrated the high sensitivity of the storm formation in the model to the analysis of the initial moisture field. The relative humidity from the GFDL FGGE data set was favorable for storm genesis, but the lower humidity from the ECMWF data set was unfavorable.

Hurricane Meli, 1979, in the South Pacific presents a case of genesis in the environment of westerly vertical shear. As shown in Fig. 7.1, the model successfully simulated the genesis of Meli. In this case, the initial eastward movement of the low level disturbance well matched the upper level westerly flow. Such a behavior is consistent with the hypothesis that vertical coupling is important for the genesis of a tropical storm. A loop in the simulated track of Meli is similar to a loop of the best track. (Note a

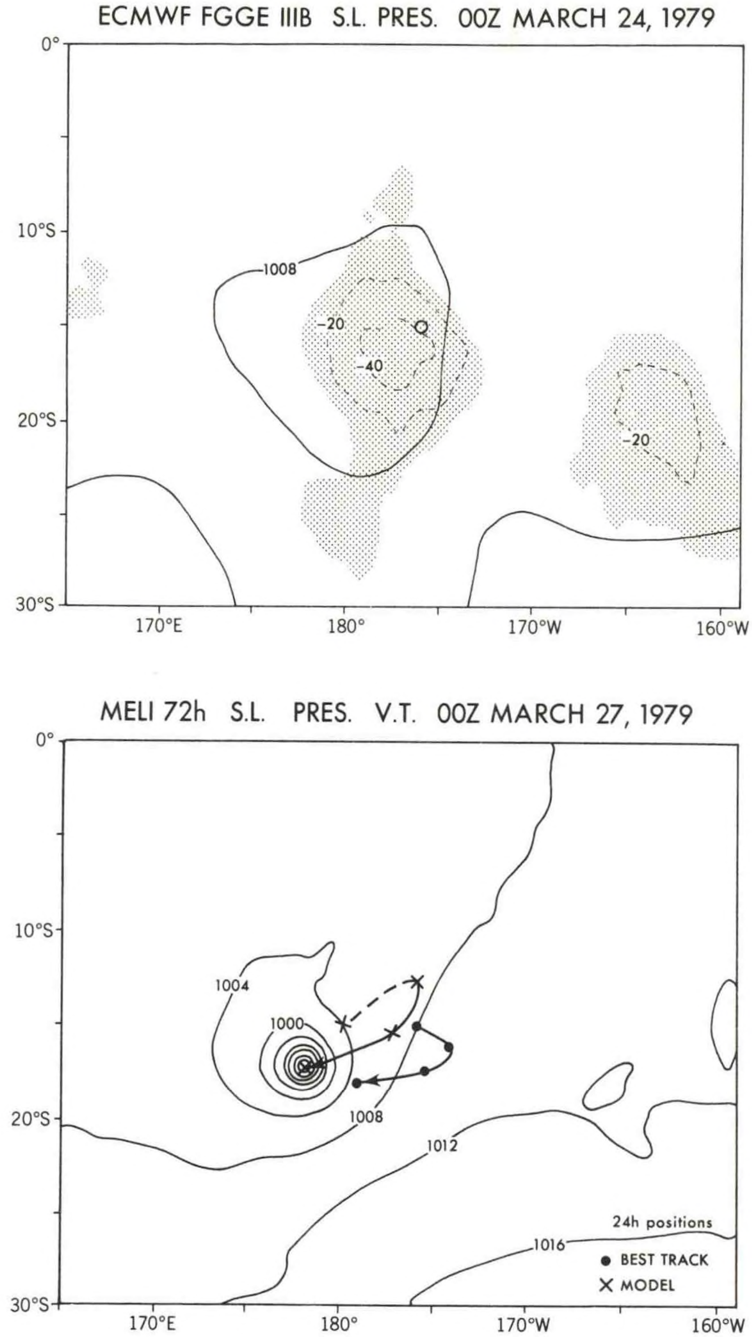

Fig. 7.1 Simulated genesis of a tropical cyclone in the South Pacific, Meli, 1979. Top: the FGGE III-B analysis of ECMWF, 00Z March 24, 1979 (isobars in mb; shading for areas with cyclonic relative vorticity greater than $10 \times 10^{-6}\ s^{-1}$, dashed lines are for relative vorticity in $10^{-6}\ s^{-1}$; open circle indicating the initial position from the best track). Bottom: a strong cyclone evolved in the model at 00Z, March 27 (storm track in the model and the best track being respectively shown. Note a difference in the initial positions, i.e., the first marks on the tracks, between the FGGE analysis and the observation.)

difference of initial positions between the analysis and observation.) It was found that the looping corresponded very well to the time change of the deep layer mean wind field.

PLANS FY89

The simulation study of Hurricane Hazel will continue.

7.2 MODEL IMPROVEMENT

M. A. Bender   Y. Kurihara
M. DiPaola   R. E. Tuleya
C. L. Kerr

ACTIVITIES FY88

7.2.1 Initialization Scheme

A diabatic initialization scheme has been developed using the idea of bounded tendency. The scheme is being tested with a triply nested mesh model. Supertyphoon TIP, 1979, was initialized and a test integration of the model was carried out. It was shown that the test integration started with less noise compared to an integration from a non-initialized condition.

Investigation of various techniques has been made to incorporate the effect of bounded tendency of wind in the initialization of the boundary layer wind. It seemed practical first to obtain the balanced wind in the Ekman-inertia regime and, then, to utilize it for computing an additional frictional-isallobaric wind component.

It was found that an application of the moisture budget equation to the moisture initialization did not always yield a reasonable initial field. This is because the moisture balance in the boundary layer is quite sensitive to the estimate of vertical diffusion at the top of the boundary layer. A more stable scheme for moisture field initialization has been formulated. In the new scheme, a reference moisture field is derived from an estimated Bowen ratio. Figure 2 shows that, in the time scale of a month, the Bowen ratio can empirically be expressed reasonably well in terms of the surface temperature and the air-sea temperature difference. The reference state thus obtained is disturbed by the vertical motion to produce an initial moisture field.

7.2.2 Time Integration and Analysis

A study of an open lateral boundary condition to be used in the time integration of a regional model has continued. After formulation and test of a number of methods, a scheme was found which could treat propagations of a wave and a vortex extremely well in a 96 hour model integration. In the scheme, both values and gradients of a field of a global model are utilized to constrain the boundary points of a regional model.

Various analysis programs were improved or prepared. They include graphics to produce a hurricane track chart and to draw vertical profiles. Also, the program to make analysis onto nested grids was developed.

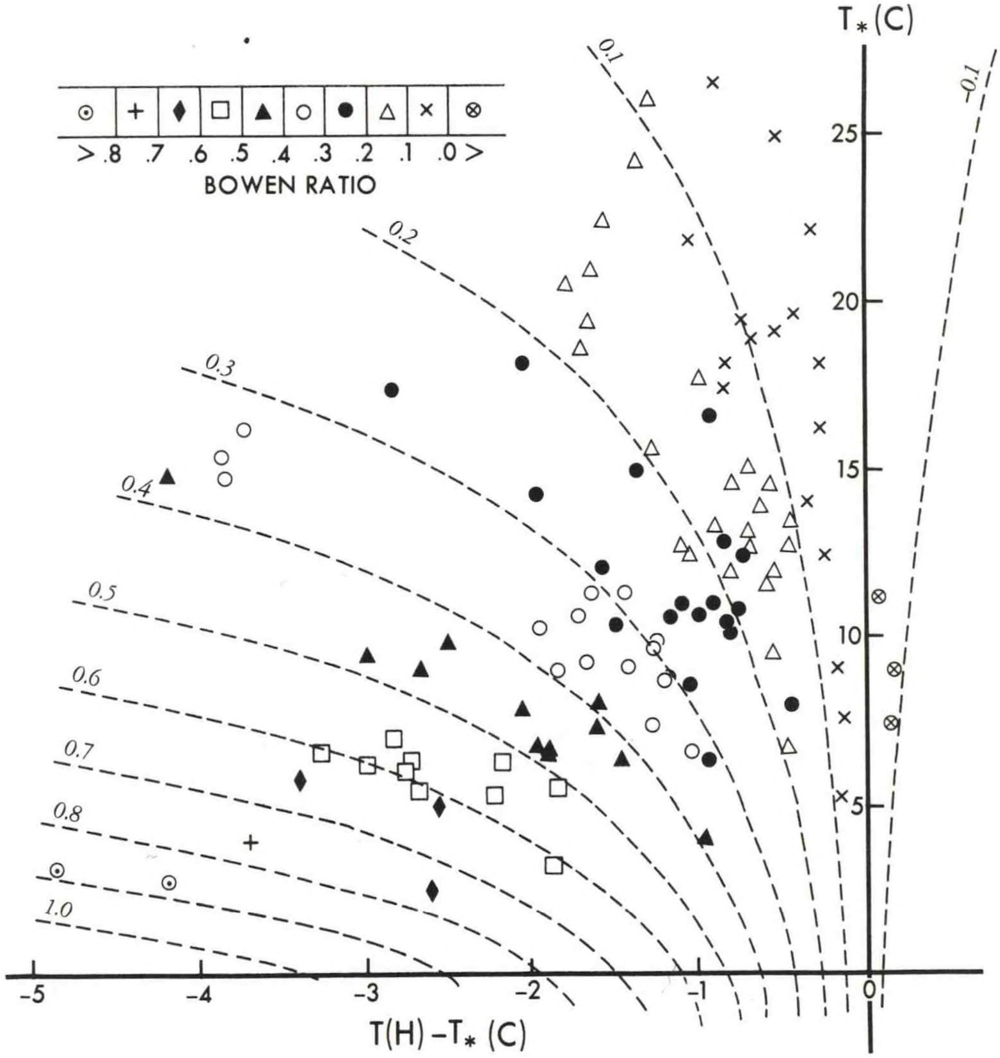

Fig. 7.2 Plotted are marks indicating the Bowen ratio, categorized into ten different value ranges, against the sea surface temperature (ordinate) and the air-sea temperature difference (abscissa). Data used for plotting (108 plots in total) are monthly statistics given for each of the nine weather ship stations in the Atlantic. Monthly figures are averages derived from daily values in respective months in a period of 10-19 years. Dashed lines are the contours of Bowen ratio which was estimated by an empirical formula as a function of sea surface temperature and air-sea temperature difference.

PLANS FY89

Initialization schemes will further be tested with real data sets. Documentation of the method will be made.

An effort will be made for the improvement of the hurricane model, including the implementation of new open lateral boundary conditions. Preliminary work related to the inclusion and assessment of radiation effects may be made.

7.3 EXPERIMENTAL HURRICANE PREDICTION

M. A. Bender W. F. Stern
C. L. Kerr R. E. Tuleya
Y. Kurihara

ACTIVITIES FY88

7.3.1 Cooperation with the National Meteorological Center

Conversion of the GFDL hurricane research model to an operational MMM (Multiply-nested Movable Mesh) model has continued, with a good deal of time spent on the significant improvement of lateral boundary conditions mentioned in 7.2.2. Preparation for documentation of the MMM model has been made.

The data for Hurricane Gloria, 1985, which had been selected for a test case, were compiled at NMC from the Global Data Assimilation System using a T80 global spectral model. Unpacking of data onto a regional grid domain is underway.

A Hurricane Analysis Workshop was held to discuss current problems and future direction of tropical analysis, in particular that of hurricanes.

7.3.2 A Supertyphoon

The first experimental prediction in a nested mesh model was successfully performed for Supertyphoon Tip, 1979. Results from two integrations, the one with the triply nested mesh (1°, 1/3°, 1/6° resolution) and the other with 1° resolution, showed distinctly superior performance by the nested-mesh model in predicting the movement, intensity change and the structure such as positions of surface maximum winds.

PLANS FY89

Experimental prediction of Hurricane Gloria will be conducted. Performance skill of the MMM model will be evaluated.

8. MESOSCALE DYNAMICS

GOALS

* To produce accurate numerical simulations of mesoscale processes in order to understand what role synoptic scale parameters play in their generation and evolution.

* To understand the dynamics of mesoscale phenomena and their interaction with larger and smaller scales.

* To determine practical limits of mesoscale predictability by means of sensitivity studies on numerical simulations of mesoscale phenomena.

8.1 THE GENERATION OF MESO-CYCLONES

I. Held   I. Orlanski
N. Nakamura   L. Polinsky

ACTIVITIES FY88

8.1.1 Mesoscale Baroclinic Instability

A numerical study has been completed to investigate the three-dimensional characteristics of the life cycle of baroclinic instability for an idealized basic state. Both meridional mixing of the temperature gradient and enhancement of the static stability by the growing wave act to stabilize the environment, and thus lead to the saturation of the wave amplitude. It was energetically confirmed that the enhancement of static stability increases its significance relative to the horizontal mixing as the horizontal scale of the wave decreases (or the characteristic Richardson number is reduced).

When the initial baroclinic zone is sufficiently large, it tends to split in two after the equilibration of the primary wave (Figure 8.1). This leads to multiple storm tracks of secondary instabilities, but the horizontal size of the individual eddies remains more or less isotropic. These aspects, absent in the previous two-dimensional study (it), imply the limited applicability of 2-D models to the real atmosphere.

Realistic features of warm and cold fronts also appear in the solutions, but they were found to be rather sensitive to the configuration of the initial basic flow.

8.1.2 Polar Lows

A study to investigate cold air cyclones, known as polar lows, is continuing. To date, a simulation of a polar low which occurred in the Gulf of Alaska during the period of 12-14 March 1985 has been completed. Results from this simulation are being compared with observations, including dropwindsonde soundings taken by a research team from ERL's Pacific Marine Environmental Laboratory. A new simulation, now being prepared, will simulate a polar low which occurred in the northeastern Pacific on 6-8 December 1987. These two studies use the NMC operational analysis for the initial and lateral boundary conditions, whereas a previous simulation (615) of a polar low which occurred during 11-12 January 1979 used the FGGE analysis.

A numerical investigation has also been started in Argentina to simulate a cyclone that occurred over the Palmer Peninsula of Antarctica on 5 September 1987. Preliminary results show very strong convection developing in the model simulation at a location coincident with the maximum in vertical velocity as indicated by ECMWF analyses.

PLANS FY89

Investigation of the polar low simulations will continue, including sensitivity studies to determine the nature of the processes that control cyclonic development. Also, a study will be performed to investigate the

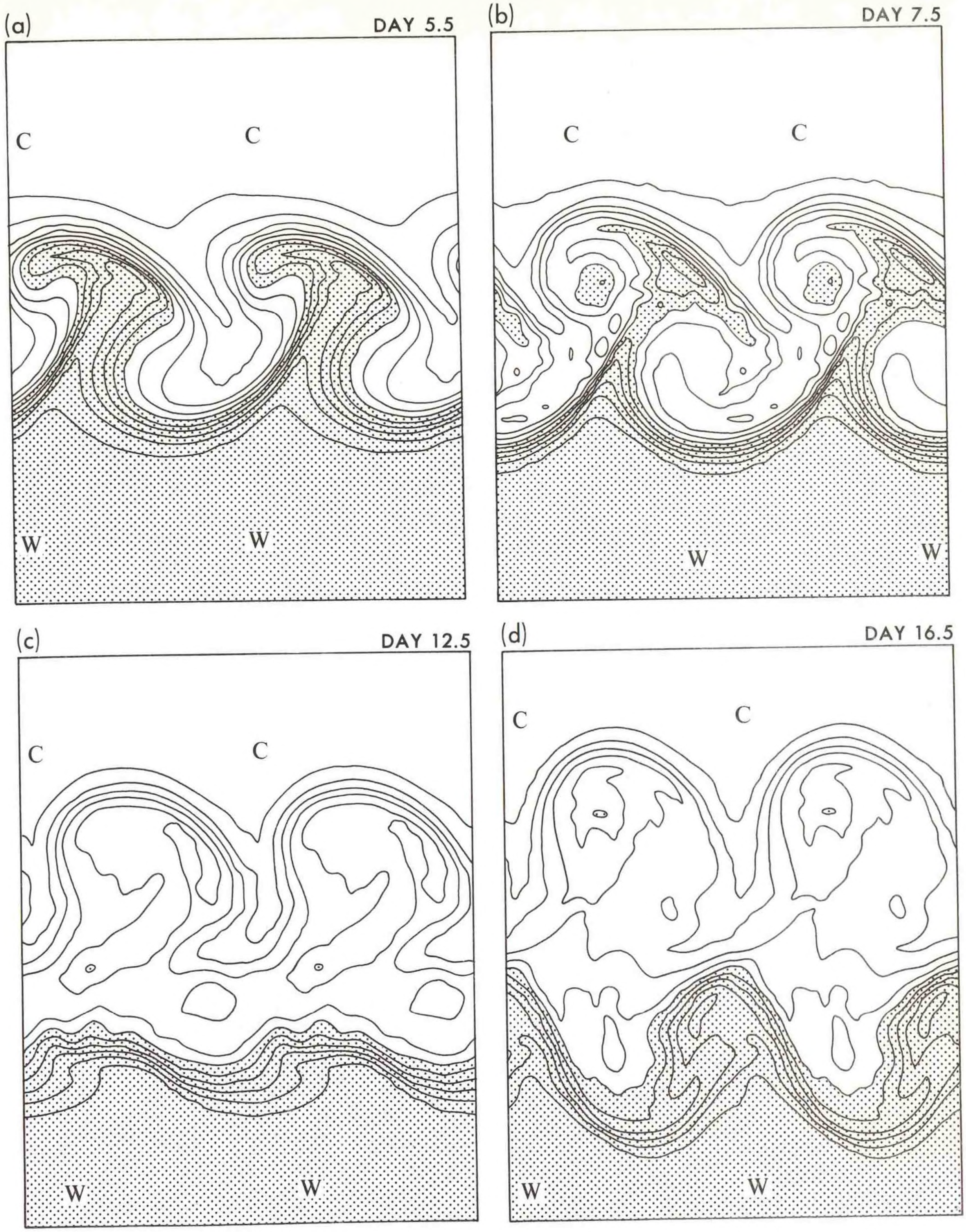

Fig. 8.1. Surface potential temperature fields associated with a growing baroclinic wave. Contour interval is 0.5K. The letters "W" and "C" denote warm and cold centers respectively. The warm air mass is stippled. The wave length is 2000 m with two wave lengths shown. a) Day 5.5: growing stage with warm and cold fronts evident. b) Day 7.5: occluding stage with warm sector being squeezed. c) Day 12.5: occluded stage with meridionally split baroclinic zones. d) Day 16.5: development of secondary instabilities within the separated baroclinic zones.

quality of global forecasts of these storms as produced by world meteorological centers.

8.2 COASTAL CYCLOGENESIS

J. Katzfey I. Orlanski

ACTIVITIES FY88

Analysis of the dynamics for the Presidents' Day cyclone of 18-19 February 1979 was completed (845, 865) using the 50-km horizontal resolution Limited-Area HIBU Model (LAHM). Two stages of development were simulated by the model. The first stage occurred as a shallow baroclinic wave that developed along the coastal front within a region of synoptic scale forcing. As the storm developed and moisture converged into the low, latent heating became important and the storm developed vertically. The flow of air ahead of this coastal cyclone fed into the region where a shortwave was approaching the coast, aiding the rapid development of the cyclone during the second stage.

A study of the sensitivity of the model simulation to latent heating and to surface fluxes has been completed. It was shown that, although latent heating and, to a lesser degree, surface heating were important to describe the intensity of the storm, the factors causing the initial development were present independent of these heating effects.

LAHM simulations of the period 25-28 January during GALE have been completed using the RAFS 2.5° analysis as initial and boundary data. The model successfully predicts the development of a long coastal front along the eastern seaboard of the United States. With the general flow of air parallel to the coastal front and its quasi-stationary nature, the coastal front assumed characteristics more typical of synoptic fronts. In particular, as a weak baroclinic wave developed along the front and moved northward along it, the "coastal" front moved offshore. As a consequence, the development of a cyclone associated with an upper level wave approaching the coast was delayed 12-18 hours until the wave reached the low level baroclinicity. An additional simulation, initiated after the initial low had forced the "coastal" front offshore, did not predict the subsequent development adequately, because the low level baroclinicity was poorly initialized.

PLANS FY89

Study of the role of surface and latent heat fluxes in producing explosive development of the coastal cyclone will continue. The impact of higher resolution initial data will be investigated.

8.3 MESOSCALE SYSTEMS IN THE SOUTHERN HEMISPHERE

J. Katzfey   I. Orlanski

ACTIVITIES FY88

8.3.1 Cyclogenesis in the Lee of the Andes

Cyclogenesis in the lee of the Andes Mountains is under investigation using the Limited-Area HIBU Model. These cyclones have not been studied extensively, although they strongly influence the weather and climate of the region. The model results will help our understanding of weather phenomena which are poorly observed due to a lack of high density, quality observations.

Analysis of high resolution simulations of cyclogenesis in South America show three stages of development: a) initial baroclinic development over the eastern Pacific Ocean, b) decay of the system as it crosses the southern tip of South America, and c) redevelopment as the storm moves over the Atlantic Ocean. Thus, the Andes Mountain chain appears to have an inhibitory effect on cyclogenesis, in contrast to other mountain chains. This also questions the accuracy of the low resolution global model predictions which produce lee cyclogenesis in this region.

8.3.2 The Effect of Cyclones on Ozone Transport

A study is being carried out on the impact of cyclone activity on ozone transport in high latitudes of the southern hemisphere. This study suggests that cyclonic activity may enhance and sharpen gradients of any tracer, such as ozone, that decreases toward the South Pole. It has also been shown that the event on 5 September 1987, which is a classic example of a strong cyclonic development, exhibits a strong correlation with low column-integrated ozone concentrations in the region. Finally, on the basis of the ECMWF global analyses of 1979 and 1982-85, it appears that there has been an upward trend during recent years in the number of cyclones that occur in the spring season south of 60°S. This trend may be correlated with the constant decrease in the Antarctic ozone layer over this period.

PLANS FY89

Additional cases of austral cyclogenesis in the lee of the Andes Mountains will be investigated. Sensitivity studies will be done to study the factors important for their development.

8.4 CHARACTERISTICS OF CONVECTION WITHIN MESOSCALE SYSTEMS

R. Hemler I. Orlanski
J. Katzfey B. Ross
F. Lipps

ACTIVITIES FY88

8.4.1 Squall Lines

Collaborative research is being carried out with the GFDL Convection Group to investigate the dynamics of convective systems using a nonhydrostatic cloud model that is nested within a hydrostatic mesoscale model. An analysis is currently being made of cloud-model simulations (866) of the squall line and super-cell convection that occurred on 10-11 April 1979 during the SESAME Experiment. Boundary conditions for these nested runs were obtained from a higher resolution version of the mesoscale simulation (836) for this case.

8.4.2 Convective Parameterization

A study was initiated to test the effect of different convective parameterizations on the distribution of heating, the accuracy and distribution of precipitation amounts and the vertical redistribution of moisture. The parameterization schemes currently implemented in the LAHM are: moist convective adjustment, Arakawa-Schubert convective parameterization, and explicit convection.

Results indicate that the Arakawa-Schubert scheme performs better than the other schemes. The Arakawa-Schubert scheme produces the smoothest distribution of precipitation, followed by moist convective adjustment and finally explicit convection. This appears to be a consequence of the way in which each parameterization treats the convective instability.

PLANS FY89

Analysis of the SESAME nested-grid simulations will be completed. Further studies will be made of the dynamics of convective systems using cloud-scale/mesoscale nesting.

Further investigation of the impact of moist convective parameterizations on the LAHM predictions will be done.

8.5 MESOSCALE FOUR-DIMENSIONAL DATA ASSIMILATION

I. Orlanski B. Ross
L. Polinsky

ACTIVITIES FY88

An on-going numerical study is being carried out to investigate techniques for assimilating standard, synoptic and nonstandard, asynoptic mesoscale data into limited-area numerical models. This study employs fraternal-twin model simulations of the Presidents' Day Snowstorm period, 18-20 February 1979. A reference atmosphere is generated using the pressure-based sigma-coordinate LAHM model (845) with a 38-km resolution, while the z-coordinate MAC/BES (Meso-Alpha Scale/Meso-Beta Scale) mesoscale model with a 50-km resolution is used as the forecast model. The technique of intermittent insertion is employed to insert data into the forecast model using a Barnes-type objective analysis. The inserted data as well as the initial and boundary data used in the forecast model are derived from simulated sounding "observations" that are obtained from the LAHM-generated reference atmosphere.

Results from initial data-assimilation experiments demonstrate the efficacy of the forecast/assimilation technique but suggest that lateral boundary effects may still play a dominant role in controlling the forecast solution, even with interior data insertion. This finding is consistent with the results from earlier research on limited-area model predictability (686).

PLANS FY89

Data assimilation experiments will be continued in order to evaluate the intermittent insertion technique and to test the effect on the forecast from the addition of wind and/or thermodynamic data that would be representative of a network of wind and radiometric profilers.

8.6 MODEL DEVELOPMENT

J. Katzfey L. Polinsky
I. Orlanski B. Ross

ACTIVITIES FY88

The LAHM has continued to be further vectorized to decrease run time. Implementation of E4 physics has been started as well as an improved, more efficient radiation package. The analysis package has been expanded. A new version of the Eta/LAHM model has been obtained from NMC. The model includes level 2.5 Mellor-Yamada turbulent diffusion, Betts convection, and the capability to run in step-mountain ("Eta") coordinates.

The MAC/BES mesoscale model has been modified to implement vertical coordinate stretching with implicit vertical diffusion and a more complete boundary layer treatment. Also, both the MAC/BES model and the analysis codes used in the data assimilation cycle (Section 8.5) have been combined and streamlined so that repeated forecast/assimilation cycles may be performed in a single job.

The hybrid version of the GFDL 2-D mesoscale model has been extended to include a full terrain-following coordinate in the lower domain. This model employs a pressure-based sigma coordinate region above the primary model domain that uses a physical height coordinate. The associated Cyber 170 analysis package has been modified to treat this terrain-following coordinate.

PLANS FY89

Improvements in the LAHM will continue through vectorization and more sophisticated physics. Comparisons of the new Eta model and the old LAHM will be done for both speed and accuracy. In addition, testing of the Eta coordinate feature will be initiated. The LAHM analysis package will continue to be improved.

The 2-D hybrid mesoscale model will be modified with the goal of incorporating it into the MAC/BES model. Corresponding modifications will be made to the initialization and analysis programs.

9. CONVECTION AND TURBULENCE

GOALS

* To develop and improve three-dimensional numerical models capable of simulating dry and moist thermal convection in the atmosphere.

* To understand the dynamics of deep moist convection and its role in the vertical transfer of heat, moisture, momentum and atmospheric tracers.

* To develop numerical models capable of simulating turbulence in homogeneous and stratified fluids by simulating the large turbulent eddies directly and by testing various parameterizations of the subgrid-scale flow.

9.1 MODEL DEVELOPMENT

R.S. Hemler
F.B. Lipps

9.1.1 Modification of Finite Difference Scheme

An attempt was made to continue the integration of a two-dimensional convection model with tritium as a passive tracer. This model and its 10 hour integration were described in (GFDL Activities FY87, Plans FY88). At 16 hours a short-wave instability developed in the tops of stratoform clouds near 10 km above the ocean surface. Furthermore, a long-wave instability was developing in the clear air at lower levels. It was found that these instabilities were associated with the Crowley scheme used to finite difference the potential temperature equation and the modified Crowley scheme used for the water vapor mixing ratio equation. Thus it was decided to use a leap-frog finite difference scheme for these equations, analogous to the scheme used for the momentum equations. This change successfully eliminated both instabilities. With the Crowley scheme using a time step of 10 seconds, the long-wave instability results in values of maximum vertical velocity of 10 m s^{-1} in the absence of convection. For the leap-frog scheme, the vertical velocity is 0.5 m s^{-1} or less.

In order to limit the development of negative values of water vapor mixing ratio with the leap-frog scheme, a vertical diffusion term is added to this equation when downward motion is present. This vertical diffusion of water vapor mixing ratio is set proportional to its gradient, so that this term is most effective in regions with strong vertical gradient and downward motion, just where negative values tend to be generated. In regions of weak vertical gradient this term is set equal to zero. This scheme has proved to be effective in eliminating negative values of water vapor mixing ratio in the three-dimensional continental squall line simulation described in Section 9.2.

In order to compare the robustness of the new scheme with the earlier Crowley scheme, a set of four-hour two-dimensional simulations were carried out. These calculations had periodic lateral boundary conditions and successively longer channel lengths. The channel lengths were multiples of 128 km, with the longest channel being 1024 km. The initial disturbance was the same in each case. Using the Crowley scheme no instabilities were evident; however, the flow patterns began to diverge after 90 minutes into the simulations. For the new scheme, there was convergence out to 3 hours for the three longest channel lengths. Also these calculations remained very similar in appearance out to 4 hours, the end of the simulations. Thus the new model produces results which are much more internally consistent.

Because of the more realistic features of the new model and in order to have results consistent with future calculations, it was decided to integrate with the new model the squall line simulations discussed in (GFDL Activities FY87, Plans FY88). These calculations are described in Section 9.2.

9.1.2 Inclusion of Ice in the Bulk Cloud Physics

A simplified bulk cloud physics has been developed which includes water vapor, cloud water/ice, rain water and ice-snow particles. The motivation for this scheme is to study the circulation in a long trailing anvil for which the presence of rain water and the heavier ice particles is expected to be a minimum. This scheme is most likely to be relevant to tropical convection and is applied to the simulation of an African squall line as described in Section 9.3.

The cloud water/ice phase moves with the air and is cloud water for temperature warmer than -6°C. For temperatures colder than -12°C it is cloud ice, and for temperatures in between it is a mixture of the two. The ice-snow phase has a density (0.1 g cm^{-3}) and relative fall velocity appropriate to snow. This phase is assumed to initially form from the autoconversion of cloud ice and to increase from accretion of cloud water/ice and depositional growth. When the temperature is above freezing, this phase melts to form rain water. The simplifying assumption is made that there is no accretion of rain by ice-snow and vice versa. Also the rain phase is not allowed to interact with the cloud ice. For the interactions allowed, the present bulk cloud physics scheme generally follows that described by Lin et al. (1983).[1]

PLANS FY89

The bulk cloud physics with the ice phase is presently included in a two-dimensional model. This scheme will be incorporated into a three-dimensional squall line model.

9.2 STATISTICS OF MOIST CONVECTION

R.S. Hemler
F.B. Lipps

ACTIVITIES FY88

Numerical simulations of a continental and a maritime tropical squall line have been carried out using the new model described in Section 9.1.1. A detailed analysis of in-cloud and out-of-cloud vertical fluxes of mass, heat, water vapor and momentum is being performed following the similar analysis given in (742). The intent of obtaining these statistics for both cases is to provide relevant information for cumulus parameterization in larger-scale models.

The horizontal domain of the model is 96 km long perpendicular to the squall line and is 32 km wide parallel to the line. Open lateral boundary conditions are applied upstream and downstream of the line and periodicity is applied on the long sides of the model domain. The horizontal grid length is 1.0 km. For the continental case the vertical grid spacing is 0.5 km and for

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[1]Lin, Y.-L., R. D. Farley and H. D. Orville, 1983 (J. Climate and Applied Meteorology, 22, 1065-1092.

the tropical line the vertical resolution is 0.25 km. Both calculations are initiated with a warm saturated bubble and are integrated for a total of four hours. The above statistics are calculated during the last two hours of these simulations when well defined squall lines were present.

PLANS FY89

The analysis of the statistics for both squall lines will be completed. A primary goal of this investigation is to determine the differences and similarities between the two lines. A study will be carried out to determine the effect of horizontal grid resolution on this type of analysis. Then this analysis will be applied to the 400 km x 400 km nested grid model described in (866) with a 5 km horizontal grid resolution.

9.3 SIMULATION OF AN AFRICAN SQUALL LINE

R.S. Hemler
F.B. Lipps

ACTIVITIES FY88

Two-dimensional numerical simulations have been carried out for the African squall line observed on 22 June 1981 during the COPT 81 (Convection Profonde Tropicale) experiment. This line had a total lifetime of at least 30 hours during which it propagated to the west with a mean speed of 14 m s^{-1}. The line consisted of a leading edge with warm rain cells followed by a weak echo region and then a long trailing anvil. A significant feature of this line was the 3 km depth of the strong rear-to-front flow behind the leading updraft. The frontal passage was associated with a 4K temperature drop and a 2 mb pressure rise. The total rainfall was approximately 2.7 cm.

The two-dimensional simulations of this line have been performed with/without the inclusion of the simplified ice bulk cloud physics described in Section 9.1.2. Calculations discussed here are for a model domain 512 km in length and 16 km in vertical extent. The convection is initiated by a cooling rate of 0.03 K s^{-1}, applied during the first 8 minutes, over a vertical depth of 3 km near the eastern end of the channel. For both model simulations, integrations were continued for a total time of 10 hours.

The model with the ice phase gave a mean propagation speed of the line of 14 m s^{-1} for the last 4 hours of the simulation and a maximum propagation speed of 15 m s^{-1}. These values are 1.5 m s^{-1} larger than for the warm rain model. As might be anticipated, the model with the ice included also gave a more realistic simulation of the trailing anvil. For this model, a mesoscale reflectivity trough was present 35-50 km behind the leading edge with stronger downward motion in this region. Anvil rain existed to a distance of 140 km behind the front whereas for the warm rain model the corresponding distance was 85 km. The model with ice included also simulated the region with 3 km deep rear-to-front flow beneath the anvil. Both models gave a 4 K temperature drop behind the front and peak values of surface rain greater than 2 cm.

A deficiency of the present simulations is that the convection is weaker than observed. This is seen perhaps most clearly in the pressure rise behind the front. Both simulations give a pressure rise of 0.5 mb, whereas the observed was 2 mb. In general, the vertical updrafts and the horizontal winds at the front are weaker in the models than the atmosphere. In both calculations, the increasing depth of the convection behind the leading edge made an angle of approximately 22° with the horizontal. For the observed line this angle was 35°.

PLANS FY89

The analysis of both simulations will be completed. It is possible that the convection is weaker than observed due to the artificial two-dimensional constraint of the calculations. For this reason three-dimensional simulations with a small width parallel to the squall line will be carried out.

9.4 PASSIVE TRACER STUDY

R.S. Hemler F.B. Lipps
H. Levy II J.D. Mahlman

ACTIVITIES FY88

The project undertaken last year to study the transfer of tritium from the stratosphere to the ocean surface has been continued using the new cloud model described in Section 9.1.1. Observational data suggest that one-third of the tritium entering the ocean is associated with rain water and two-thirds with vapor diffusion.

A key factor in determining the downward flux of tritium is the speed at which tritium is able to escape from falling precipitation. In order to show the importance of this effect, three different calculations are carried out. For the first calculation, denoted as Case T, thermodynamic equilibrium is assumed between the falling rain and the environment. In the second calculation, denoted as Case E, the concentration of tritium in the rain water is assumed to remain constant during evaporation. For this case as for frozen precipitation, the tritium that enters the atmosphere is the tritium contained in the surface layers of the raindrops (ice particles) that evaporate. Thus the third calculation is a crude attempt to represent the transfer of tritium into the atmosphere when frozen particles exist above the freezing level at 4.5 km and rain water exists below this level. In this calculation, denoted as Case ET, the transfer of tritium above the freezing level is calculated as in Case E and below this level it is calculated as in Case T.

Two-dimensional numerical calculations have been carried out for these three cases using a maritime tropical base state. These calculations were integrated for a period of 24 hours. The model domain has a length of 64 km and a vertical extent of 25 km. The initial tritium mixing ratio is constant above 13.25 km and decreases rapidly below this level. The convection is initiated by a boundary layer moisture disturbance which is applied during the first two hours and again between four to six hours into the integration.

For all three cases the deposition of tritium into the ocean by rainout stopped at 7 hours, when precipitation due to the second boundary layer forcing stopped. Deposition of tritium into the ocean by vapor diffusion, however, continued for the full 24 hours. These aspects of the tritium deposition for Case ET are shown in Fig. 9.1. At 12 hours the ratio of deposition by vapor diffusion to deposition by rainout is 0.60. Due to the continued deposition by vapor diffusion as seen in Fig. 9.1a, this ratio is 2.93 by 24 hours. In Fig. 9.1b the amount of tritium in the boundary layer appears to vary little over the second 12 hours of this calculation. It is seen that the total tritium deposition over 24 hours is very small. This will be a topic for future investigation.

For Case T the ratio of deposition by vapor diffusion to deposition by rainout at 24 hours is 3.80 while for Case E the corresponding ratio is 0.60. In Case E, however, 20 times as much tritium was deposited into the ocean as for Case T and 10 times as much as for Case ET. This result occurs since the loss of tritium by the falling raindrops is much more efficient in Case T where thermodynamic equilibrium is assumed. Thus in Case T most of the tritium captured by the rain water returns to the atmosphere at upper levels. For Case E much more of the tritium reaches lower levels and enters the ocean by rainout. These three cases emphasize the sensitivity of the present results to the role of the falling precipitation.

Three-dimensional calculations for an insoluble tracer, a fully soluble tracer and a partially soluble tracer (SO_2 gas) have been carried out using the continental and maritime tropical squall line models discussed in Section 9.2. The initial distribution of tracer is a constant mixing ratio in the surface boundary layer and zero above, for all three types of tracer. The analysis of results for both types of squall lines is underway.

PLANS FY89

The tritium calculations for Case ET will be continued. Calculations for a second day will be carried out, using the same convection model as for the first day but with the initial distribution of tritium being the vertical mean profile at the end of the first day. It is thought that this calculation will result in a much larger deposition of tritium into the ocean. The sensitivity of Case ET to the form of the initial moisture disturbance will also be examined.

The analysis of the three-dimensional squall line calculations with the three types of passive tracer will be completed.

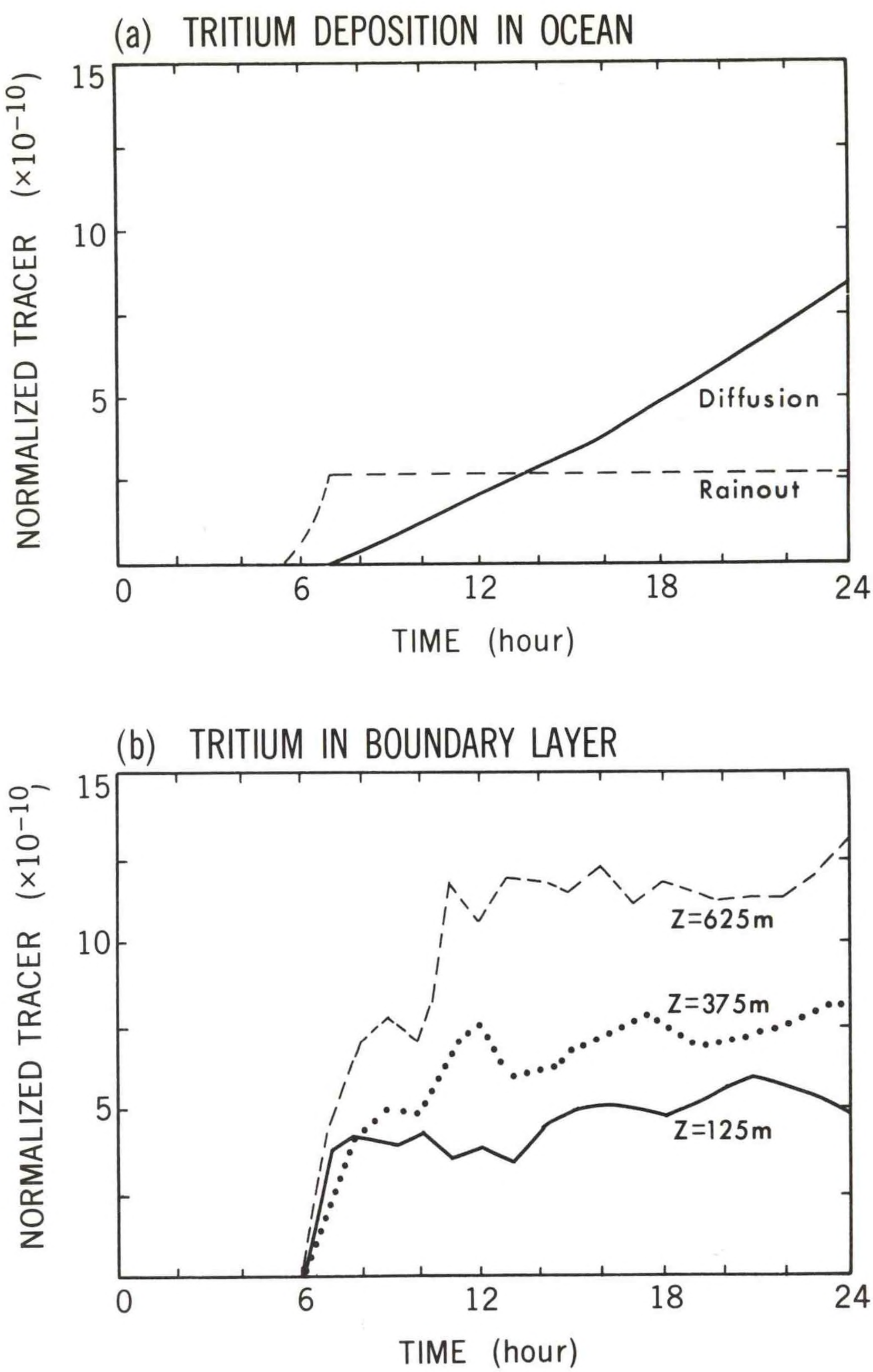

Fig. 9.1 Time history for Case ET. (a) Tritium deposition into ocean by vapor diffusion (solid line) and by rainout (dashed line). Ordinate shows tritium deposition normalized by the initial total tritium in the atmosphere. (b) Normalized values of tritium in the boundary layer at z=125 m (solid line), z=375 m (dotted line) and z=625 m (dashed line).

APPENDIX A

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and

Affiliated Personnel

during

Fiscal Year 1988

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Betty M. Williams	Secretary
Douglas G. Hahn	Assistant Director
Joan M. Pege	Administrative Assistant

CLIMATE DYNAMICS

Manabe, Syukuro	Sr. Research Scientist	FTP
Broccoli, Anthony	Research Associate	FTP
Brooks, Kevin	Junior Fellow	FTP
Delworth, Thomas	Research Associate	FTP
Fels, Stephen	Sr. Research Scientist	FTP
Friedenreich, Stuart	Research Associate	FTP
Lofgren, Brent M	Student	PU
Ma, Chung-Chun	Student	PU
Ramaswamy, V.	Program Scientist	PU
Saravanan, R.	Student	PU
Schwarzkopf, M. Daniel	Sr. Research Associate	FTP
Zhu, Xun	Program Scientist	PU
Hayashi, Yoshikazu	Research Scientist	FTP
Golder, Donald	Sr. Research Associate	FTP
Held, Isaac	Sr. Research Scientist	FTP
Cook, Kerry	Research Associate	PTP
Feldstein, Steven	Program Scientist	PU*
Fyfe, John	Program Scientist	PU
Huot, Jean-Paul	Student	PU*
Lee, Sukyoung	Student	PU
O'Brien, Enda W.	Program Scientist	PU
Phillipps, Peter	Research Associate	FTP
Ting, Mingfang	Student	PU
Sheng, Jian	Program Scientist	PU*
Spelman, Michael	Sr. Research Associate	FTP
Daniel, Donahue	Research Associate	FTP*
Stouffer, Ronald	Sr. Research Associate	FTP
Wetherald, Richard	Sr. Research Associate	FTP

MIDDLE ATMOSPHERE DYNAMICS AND CHEMISTRY

Mahlman, Jerry D.	Sr. Research Scientist	FTP
Hamilton, Kevin P.	Program Scientist	PU
Kida, Hideji	Program Scientist	PU*
Levy, Hiram II	Research Scientist	FTP
Black, Charles	Georgia Tech Research Aid	RA
Kasabhatla, Prasad	Georgia Tech Res. Associate	RA
Moxim, Walter J.	Sr. Research Associate	FTP
Pinto, Joseph P.	Program Scientist	PU
Pitari, Giovanni	Program Scientist	PU*
Tao, Xin	Student	PU
Umscheid, Ludwig J.	Sr. Research Associate	FTP
Fesenko, John	Junior Fellow	FTP

*Affiliation Terminated Prior to September 30, 1988

EXPERIMENTAL PREDICTION

Miyakoda, Kikuro	Sr. Research Scientist	FTP
Chao, Yi	Student	PU
Derber, John	Assoc. Research Scientist	FTT
Gordon, Charles T.	Research Scientist	FTP
Gudgel, Richard G.	Research Associate	FTP
Manzini, Eliza	Student	PU
Pierrehumbert, Raymond T.	Research Scientist	PTP*
Anderson, Jeffrey	Student	PU
Lin, Shian-Jiann	Student	PU
Ploshay, Jeffrey	Research Associate	FTP
Rosati, Anthony	Sr. Research Associate	FTP
Sirutis, Joseph	Sr. Research Associate	FTP
Stern, William	Sr. Research Associate	FTP
Smith, Robert	Computer Operator	FTP
Wyman, Bruce	Research Associate	FTP

OCEANIC CIRCULATION

Bryan, Kirk	Sr. Research Scientist	FTP
Cox, Michael	Research Scientist	FTP
Dixon, Keith	Research Associate	FTP
Gerdes, Rudiger	Program Scientist	PU
Pond, Stephen	Program Scientist	PU*
Samuels, Bonita	Research Associate	FTP
Toggweiler, John R.	Assoc. Research Scientist	FTT
Philander, Samuel G.H.	Sr. Research Scientist	FTP
Chai, Fei	Student	PU
Chang, Ping	Student	PU*
Hurlin, William	Research Associate	FTP
Matano, Ricardo P.	Student	PU
Pacanowski, Ronald	Sr. Research Associate	FTP

PLANETARY CIRCULATIONS

Williams, Gareth	Sr. Research Scientist	FTP
Wilson, R. John	Research Associate	FTP

*Affiliation Terminated Prior to September 30, 1988

OBSERVATIONAL STUDIES

Oort, Abraham	Sr. Research Scientist	FTP
Karoly, David J.	Program Scientist	PU
Lau, Ngar-Cheung	Research Scientist	FTP
Kushnir, Yochanan	Program Scientist	PU
Lau, Alexis K.-H.	Student	PU
Nath, Mary J.	Research Associate	FTP
Levitus, Sydney	Sr. Research Associate	FTP
Jackson, Martha	Sr. Technician	FTP
Rosenstein, Melvin	Sr. Technician	FTP

HURRICANE DYNAMICS

Kurihara, Yoshio	Sr. Research Scientist	FTP
Bender, Morris A.	Sr. Research Associate	FTP
Kerr, Christopher L.	Research Associate	FTT*
Ross, Rebecca J.	Research Associate	FTT
Tuleya, Robert E.	Sr. Research Associate	FTP
DiPaola, Michael	Junior Fellow	FTP

MESOSCALE DYNAMICS

Orlanski, Isidoro	Sr. Research Scientist	PTP
Nakamura, Noburo	Student	PU*
Katzfey, Jack	Research Associate	FTP
Polinsky, Larry	Research Associate	FTP
Ross, Bruce	Research Scientist	FTP

CONVECTION AND TURBULENCE

Lipps, Frank	Research Scientist	FTP
Hemler, Richard	Research Associate	FTP

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CENTRALIZED SUPPORT SERVICES

Administrative and Technical Support

Baker, Philip	Computer Programmer Analyst	FTP
Pege, Joan	Administrative Assistant	FTP
Tunison, Philip	Supv. Scientific Illustrator	FTP
Moy, Victoria	Jr. Office Draftsman	PTT*
Raphael, Catherine	Scientific Illustrator	PTP
Varanyak, Jeffrey	Scientific Illustrator	FTP
Zadworney, Michael	Jr. Office Draftsman	FTP
Urbani, Elaine	Travel Clerk	FTP
Uveges, Frank	Supv. Computer Specialist	FTP
Amend, Beatrice	Clerk Typist	PTT
Byrne, James	Jr. Technician	FTP
Conner, John	Photographer	FTP
Williams, Betty M.	Secretary	FTP
Blessing, Mae	Library Aid	PTP
Kennedy, Joyce	Editorial Assistant	FTP
Marshall, Wendy	Editorial Assistant	FTP

Computer Systems Support

Welsh, James	Sr. Computer Sys. Analyst	FTP
Kranz, Christopher	Computer Sys. Programmer	FTT
Shaginaw, Richard	Computer Sys. Programmer	FTP*
White, Robert	Computer Sys. Programmer	FTP
Yeager, William	Computer Sys. Programmer	FTP

Computer Operational Support

Shearn, William	Operations Manager	FTP
Hopps, Frank	Supv. Computer Operator	FTP
King, John	Computer Operator	FTP
Taylor, Thomas	Computer Operator	FTP
Davis, Manuel	Peripheral Equip. Opr.	FTT
Deuringer, James	Peripheral Equip. Opr.	FTT
Haught, Darrell	Peripheral Equip. Opr.	FTT*
Sotomayor, Anibal	Junior Fellow	FTP*
Hand, Joseph	Supv. Computer Operator	FTP
Henne, Ronald	Computer Operator	FTP
Brandbergh, Gerald	Computer Operator	FTP
Cordwell, Clara	Computer Operator	FTP
Krueger, Scott	Peripheral Equip. Opr.	FTT
Heinbuch, Ernest	Supv. Computer Operator	FTP
Conover, Leonard	Computer Operator	FTP
Miller, Almore	Computer Operator	FTP

*Affiliation Terminated Prior to September 30, 1988

AOS PROGRAM

Sarmiento, Jorge	Associate Professor	PU
Amend, Beatrice E.	Clerk/Typist	PU*
Anderson, Laurence A.	Student	PU
Byers, James C.	Student	PU*
Callan, Johann V.	Secretary	PU
Gnanadesikan, Anand	Summer Student	PU*
Herbert, Timothy D.	Research Associate	PU*
Key, Robert M.	Research Staff	PU
Koehler, Nancy Duprey	Technical Specialist	PU
Murnane, Richard J.	Research Associate	PU
Najjar, Raymond G.	Student	PU
Olsen, Esther B.	Administrative Assistant	PU
Orr, James	Computer Programmer	PU
Shaffer, Gary	Program Scientist	PU*
Slater, Richard D.	Computer Programmer	PU
Thiele, Gerhard P.J.	Program Scientist	PU*
Wong, Richard	Computer Programmer	PU
Mellor, George	Professor	PU
Ang, Mung-Ling	Computer Programmer	PU*
Galperin, Boris	Research Staff	PU*
Hakkinen, Sirpa M. A.	Research Staff	PU
Kantha, Lakshmi H.	Program Scientist	PU*
Oey, Lie-Yauw	Program Scientist	PU*
Xue, Hui-Jie	Student	PU

CONTROL DATA CORPORATION

Robert Kazawic, Sales Representative

Stringer, John	Analyst in Charge	CDC
Hess-Hughes, Julie	Analyst	CDC
Reiss, Israel	Systems Analyst	CDC
Helster, Paul	Senior Engineer in Charge	CDC
Armbruster, Richard	Senior Customer Engineer	CDC*
Cerkan, John	Senior Customer Engineer	CDC
Csapo, Michael	Customer Engineer	CDC
Dorado, Manual	Senior Customer Engineer	CDC
Jones, John	Senior Customer Engineer	CDC
Smith, Alain	Senior Customer Engineer	CDC
Thompson, Robert	Senior Customer Engineer	CDC*
Valin, Chris	Customer Engineer	CDC
Weiss, Edward	Senior Customer Engineer	CDC

*Affiliation Terminated Prior to September 30, 1988

PERSONNEL SUMMARY

September 30, 1988

GFDL/NOAA

Full Time Permanent (FTP)	76
Part Time Permanent (PTP)	4
Full Time Temporary (FTT)	7
Part Time Temporary (PTT)	1
Junior Fellows	3
Research Affiliates (RA)	2

PRINCETON UNIVERSITY (PU)

Program Scientists	9
Students	16
Professors	2
Research Staff	6
Support Staff	3

CONTROL DATA CORPORATION (CDC)

Computer Support Staff	11
TOTAL	140

APPENDIX B

GFDL

Bibliography

1983-1988

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Director
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Princeton, New Jersey 08542

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APPENDIX C

Computational Support

Computational Support

The computational support at GFDL comprises three Control Data CYBER computers:

CY1, a 170/730 with 256K words of memory;
CY2, a 205 supercomputer, with 4 million words of memory; and
CY4, another 205, with 4 million words of memory.

Using the funds made available during FY87, additional memory and disk were added to the CYBER system in October, 1987. The additional memory gives CY2 and CY4 identical memory capacity. The additional disk has been deployed to give the two machines identical disk configurations.

In February, 1988, a contract was signed to provide the laboratory with an Ethernet local area network, 55 Sun-3/50 monochrome desktop workstations, and a Sun-3/160 server supporting shared disk and laser printing. The network has been installed, and it is expected that all workstations will be in use in scientists' offices by the end of FY88.

To support the workstations, hardware and software was added to the CYBER 170/730 to provide basic TCP/IP networking.

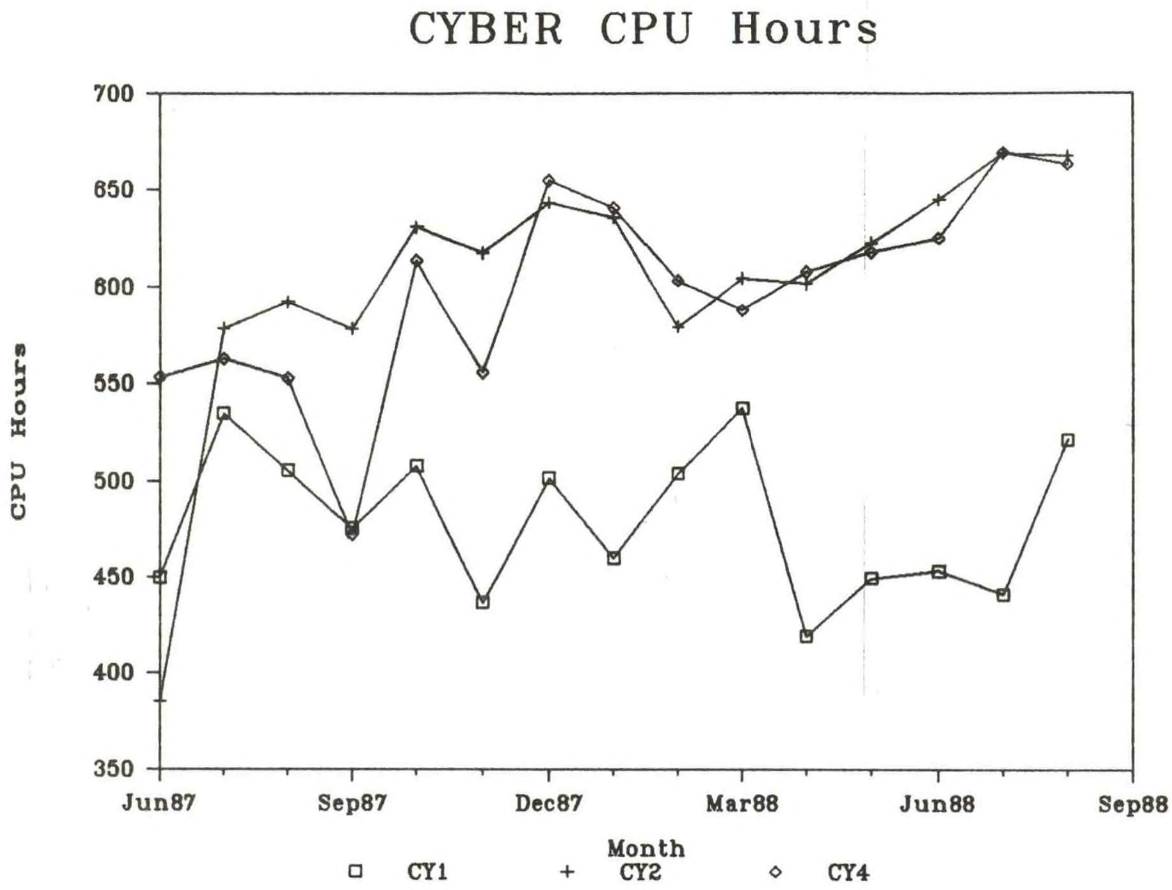
Planning for the procurement of a class VII supercomputer continued to be a central activity during FY88. Interaction with the vendors of an archival storage subsystem and a massively parallel processor resulted in further development of the technical specifications. A draft RFP and benchmark programs are now being reviewed by more than 30 computer vendors and system integrators.

The following table and figure show how many CPU hours were achieved on each machine during the period of this report.

Table C-1. Achieved CPU Hours for GFDL Machines

Month	CY1	CY2	CY4	CY2+CY4
Sep 87	476	578	472	1050
Oct 87	508	631	613	1244
Nov 87	437	617	556	1173
Dec 87	501	643	655	1298
Jan 88	460	635	640	1275
Feb 88	504	579	603	1182
Mar 88	538	604	588	1192
Apr 88	419	602	607	1209
May 88	449	622	617	1239
Jun 88	453	645	625	1270
Jul 88	441	668	669	1337
Aug 88	521	667	663	1330
Sep 88	**	**	**	**

** Not available at press time.


CYBER CPU Hours
700
650
600
550
500
450
400
350
CPU Hours
Jun87
Sep87
Dec87
Mar88
Jun88
Sep88
Month
CY1
CY2
CY4

APPENDIX D

Seminars Given at GFDL

During Fiscal Year 1988

2 September 1987	"Numerical Simulation of an Abrupt Seasonal Transition and Some Low Frequency Variations of Atmospheric Circulation" by Prof. Qin-cun Zeng, Director, Institute of Atmospheric Physics, Academia Sinica, Beijing, CHINA
10 September 1987	"A Coupled Dynamic Thermodynamic Model of the Ice-Ocean System in the Marginal Ice Zone" by Dr. Sirpa Hakkinen, NASA/Goddard SFC, Greenbelt, MD
14 September 1987	"Oceanic Uptake of Transient CO_2" by Prof. Bert Bolin, University of Stockholm, Sweden
15 September 1987	"Solitary Wave Models of Atmospheric Blocking" by Dr. Keith Haynes, Department of Physics, Imperial College, London, UK
17 September 1987	"A Hierarchy of Perturbative Models for Solving Nonlinear Problems in GFD: Systematic use of Symbolic Manipulation" Dr. Ray-Qing, Dept. of Atmospheric Science, University of California, Los Angeles, CA
21 September 1987	"The Harmonic Convergence of Climate Modelling and Parallel Computing" by Dr. Robert Chervin, National Center for Atmospheric Research, Boulder, CO
22 September 1987	"A Coupled Ice-Ocean Model" by Dr. L. Kantha and Prof. G. Mellor, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
29 September 1987	"Numerical Simulation of Deep Convection with a Nested Grid" by Dr. F. Lipps, Dr. B. Ross, and R. Hemler, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
1 October 1987	"Climate Drift in the NCAR Community Climate Model" by Dr. David L. Williamson, National Meteorological Center, Washington, DC
2 October 1987	"Semi-Lagrangian Transport of Water Vapor for a Global Spectral Model" by Dr. David Williamson, National Meteorological Center, Washington, DC
2 October 1987	"Abrupt Climate Changes Caused by Reorganizations of the Ocean - Atmosphere System" by Prof. W. S. Broecker, Lamont-Doherty Geological Observatory, Columbia University, Palisades, NY
5 October 1987	"WKB Approximate Computation of Baroclinic Instability on the Sphere" by Prof. G. Zimmermann, Johannes Gutenberg Universitat, Fachbereich Physik, Institut fur Meteorologie, Mainz, Germany

8 October 1987	"Low Frequency Current Fluctuations in the Strait Georgia, British Columbia" by Dr. Stephen Pond, University of British Columbia, Canada
15 October 1987	"Dynamics and Thermodynamics of a Model ENSO" by Mr. David Battisti, Department of Atmospheric Sciences, University of Washington, Seattle, WA
27 October 1987	"The 100 K Ice Age Cycle" by Dr. R. Toggweiler, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
28 October 1987	"South Atlantic Inter-Basin Exchange and the Global Thermohaline Circulation" by Dr. Steve Rintoul, Woods Hole Oceanographic Institution, Woods Hole, MA
29 October 1987	"Techniques for the Analysis of the Space-Time Variations of Observations or Model Simulations using Principal Evolution and Observational Patterns" by Dr. Klauss Hasselmann, Max Planck Institute, Hamburg, Germany
30 October 1987	"A Numerical Study of the Initiation and Maintenance of Squall Lines" by Dr. Andrew Crook, National Center for Atmospheric Research, Boulder, CO
5 November 1987	"Dynamics of the Antarctic Middle Atmosphere with Emphasis on Climatology and Gravity Waves" by Dr. Hiroshi Kanzawa, Department of Atmospheric Sciences, University of Washington, Seattle, WA
10 November 1987	"Simulations of the Last Glacial Maximum using an AGCM including Climatic Tracer Cycles" by Dr. Sylvie Joussaume, Laboratoire de Meteorologie Dynamique, Paris, France
18 November 1987	"Medium Range Forecasts at the ECMWF" by Dr. Lennart Bengtsson, European Center for Medium Range Weather Forecasts, Reading, Berkshire, England
19 November 1987	"Effects of Pollution on Cloud Reflectivity: Implications For Man's Impact on Climate" by Dr. James Coakley, National Center for Atmospheric Research, Boulder, CO
23 November 1987	"Radar Studies of Gravity Wave Properties in the Middle Atmosphere" by Dr. Robert A. Vincent, Physics Department, University of Adelaide, Adelaide, South Australia
24 November 1987	"2-D Transport Model for Stratospheric Species" by Dr. Xiude Lin, Aeronomy Laboratory, ERL/NOAA, Boulder, CO

30 November 1987	"Use and Misuse of Scientific Findings by the Policy Community" by Dr. William C. Clark, Kennedy School of Government, Harvard University, Cambridge, MA
1 December 1987	"Fitting Numerical Models to Observations" by Dr. Carlisle Thacker, Atlantic Oceanographic & Meteorological Laboratory, 4301 Rickenbacker Causeway, Miami, FL
1 December 1987	"Life Cycles of Baroclinic Waves" by Dr. Steven Feldstein, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
3 December 1987	"Numerical Simulations of Fields of Cumuli and Individual Cumuli at High Spatial Resolution" by Dr. Terry L. Clark, National Center for Atmospheric Research, Boulder, CO
8 December 1987	"British Columbia Fjord Circulations" by Dr. Steven Pond, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
19 January 1988	"A Result from the Trajectory Analysis on the Middle Atmospheric Motions Simulated by the SKYHI N90 Model" by Dr. H. Kida, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
2 February 1988	"Interpentadal Variability of Temperature and Salinity at Intermediate Depths of the North Atlantic Ocean: An Update" by Sydney Levitus, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
5 February 1988	"Ocean GCM Hindcasts of 1982-83 El Nino" by Dr. W. Kessler, Department of Oceanography, University of Washington, Seattle, WA
8 February 1988	"Forecast Experiments for the Summer of 1984 with the MRI.GCM-I: Sensitivity of the SST Anomalies and Cumulus Parameterizations" by Mr. Akio Kitoh, Meteorological Research Institute, Japan Meteorological Agency, Tsukuba, Japan
9 February 1988	"Geometry Forced Coherent Structures as a Model of the Kuroshio Large Meander" by Dr. T. Yamagata, Kyusha University, Kasuga, Japan
10 February 1988	"Deterministic Chaos and Monsoon Variability" by Prof. V. Satyan, Physical Research Laboratory, Ahmedabad, India
11 February 1988	"Sensitivity of Middle Eastern Precipitation Forecast to Changes in Eastern Mediterranean SST" by Dr. Stephen Brenner, Israel Oceanograpic and Limnological Research, Israel

12 February 1988 — "The Biosphere and the Global Climate System" by Dr. Piers Sellers, University of Maryland, NASA/Goddard Space Flight Center, Greenbelt, MD

16 February 1988 — "NWP Experiments using an Orographic Gravity Wave Scheme" by William Stern, Geophysical Fluid Dynamics Laboratory, Princeton, NJ

16 February 1988 — "The Bifurcation to Equatorial Super Rotation in an Atmospheric General Circulation Model" by Dr. Max Suarez, NASA/Goddard Space Flight Center, Greenbelt, MD

18 February 1988 — "Ocean Acoustic Tomography in the Greenland Sea Project" by Dr. J. F. Lynch, Woods Hole Oceanographic Institute, Woods Hole, MA

23 February 1988 — "Holocene Climate Variations (Sex, Violence, Politics, and Weather over the Last 10,000 Years) by Dr. Kevin Hamilton, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ

24 February 1988 — "Towards the Modeling of Water Balance Dynamics at the Catchment Scale" by Dr. M. Sivapalan, Civil Engineering Department, Princeton University, Princeton, NJ

2 March 1988 — "An Idealistic Circulation of the Equatorial Region Exemplified by a GCM" by Dr. Y. Y. Hayashi, Geophysical Institution, Faculty of Science, Tokyo University, Tokyo, Japan

8 March 1988 — "Quasi-Geostrophic Flow over Topography: Mean Flow Generation and Chaos" by John Allen, Princeton University Princeton, NJ

8 March 1988 — "Transport of H_2O, Gases, Organic Matter, and Trace Metals in the Soil" by Prof. K. O. Munnich, University of Heidelberg, Heidelberg, Germany

10 March 1988 — "Studies of Vertically Propagating Planetary Waves" by Dr. William Randel, National Center for Atmospheric Research, Boulder, CO

11 March 1988 — "Cloud and Air-Sea Interaction in the Tropical Region" by Dr. C. Gautier, Scripps Institute of Oceanography, La Jolla, CA

17 March 1988 — "The Operational NMC T80 MRF Model and its Performance" by Prof. Masao Kanamitsu, National Meteorological Center, Development Division, Washington, DC

18 March 1988	"Complex Quality Control of Meteorological Data" by Prof. Lev Gandin, National Meteorological Center, Development Division, Washington, DC
22 March 1988	"An Ocean Data Assimilation System, by John Derber, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
25 March 1988	"Some Simple Mechanisms of the 30-50 Day Oscillation" by Dr. R. N. Keshavamurty, Physical Research Laboratory, Navrangpura, Ahmedabad, India
1 April 1988	"Multile Equilibria and Weather Regimes: A Critical Re-Examination of a Baroclinic 2-Layer Model" by Dr. Priscilla Cehelsky, Geophysical Institute, University of Tokyo, Bunkyo-ku, Tokyo, Japan
5 April 1988	"CISK and the Madden-Julian Oscillation" by Dr. Isaac Held, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
12 April 1988	"Variational Fitting of 4-D Model Solutions to Data" by Dr. John Derber, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
15 April 1988	"Isopycnal Model of the World Ocean" by Dr. Josef Oberhuber, Max Planck Institute, Hamburg, Germany
19 April 1988	"Testing the GFDL Ocean Model with Radiocarbon" Dr. J. Toggweiler, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
20 April 1988	"The Ocean Below the Southern Sea Ice" by Prof. Arnold Gordon, Lamont-Doherty Geological Observatory, Palisades, NY
21 April 1988	"Hypercube Algorithm for Large-Scale Spectral Simulation in Fluid Dynamics" by Dr. Richard Pelz, Mechanical & Aerospace Engineering, Rutgers University, New Brunswick, NJ
22 April 1988	"Evaporation from the Amazonian Rain Forest" by Dr. W. J. Shuttleworth, Institute of Hydrology, United Kingdom
26 April 1988	"Downward Transport of Tritium Due To Deep Convection" by Dr. F. B. Lipps and R. S. Hemler, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
27 April 1988	"Oceanic Phytoplankton, Atmospheric Sulphur, Cloud Albedo and Climate" by Dr. Robert Charlson, Department of Atmospheric Sciences, University of Washington, Seattle, WA

28 April 1988	"Nonlinear Saturation of Barotropic and Baroclinic Instabilities" by Dr. Theodore Shepherd, Cambridge University, Cambraidge, England
29 April 1988	"Wave-Wave Interactions in a Stratospheric Model" by Mr. C. McLandress, McGill University, Montreal, Quebec, Canada
2 May 1988	"Austral Cyclones: A Possible Pac-Man for the Ozone Layer" by Dr. Isidoro Orlanski, Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey
3 May 1988	"Simulations of Polar Stratospheric Clouds" by Dr. V. Ramaswamy, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
6 May 1988	"A Model of Biogeochemical Cycling of Phosphorus, Nitrogen, Oxygen, and Sulphur in the Ocean: One Step Toward a Global Climate Model" by Dr. Gary Shaffer, Department of Oceanography, Gothenburg University, Goteborg, Sweden
13 May 1988	"Gravity Wave Momentum Fluxes and Anisotrophy Inferred from the MU Radar" by Dr. David Fritts, University of Alaska, Fairbanks, Alaska
17 May 1988	"Time-Dependent 3-D Model of Delaware Bay and River" by Prof. G. Mellor and Dr. B. Galperin, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
18 May 1988	"Oceanic Primary Production, Mid-Depth Denitrification, Continental Shelves and Ice Age Cycles" by Dr. Gary Shaffer, Department of Oceanography, Gothenburg University, Goteborg, Sweden
19 May 1988	"Boundary Layer Wind Adjustment and Assimilation" by Dr. John Young, Development Division, National Meteorological Center, Washington, DC
20 May 1988	"Role of Soil and Vegetation in a General Circulation Model" by Dr. R. Dickinson, National Center for Atmospheric Research, Boulder, CO
24 May 1988	"Time Scale Dependence of Wintertime Low-Frequency Variability" by Dr. Yochanan Kushnir, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ

26 May 1988	"Progress on Plans with the Regional Analysis and Forecast System at NMC" by Dr. James Hoke, National Meteorological Center, Washington, DC
31 May 1988	"Modeling the Ocean's Response to Westerly Wind Bursts" by Dr. Ben Giese, University of Washington, Seattle, WA
2 June 1988	"Smoke Dynamics and Atmospheric Residence Time in Nuclear Winter Studies" by Dr. Robert Malone, Los Alamos National Laboratory, Los Alamos, New Mexico
3 June 1988	"Scale Interaction and Predictability in a Mesoscale Model" by Dr. Andrew Van Tuyl, National Center for Atmospheric Research, Boulder, CO
7 June 1988	"Temporal Evolution of Low-Frequency Circulation Patterns" by Dr. Yochanan Kushnir, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
9 June 1988	"Little Ice Age Effects in Equatorial Upwelling: The Coral Cd Record in the Galapagos Islands" by Dr. Glenn Shenn, Lamont Doherty Geological Observatory, Palisades, NY
14 June 1988	"Tropical Stationary Wave Response to Zonally-Asymmetric SST in an Idealized GCM" by M. Ting, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
17 June 1988	"Analysis of Global Sea Level Variations Using GEOSAT Data, by Dr. Chester Koblinsky, Geodynamics Branch, NASA/Goddard Space Flight Center, Greenbelt, MD
27 June 1988	"Cloud Forcing: Observational and Modeling Studies, by Dr. J. T. Kiehl, National Center for Atmospheric Research, Boulder, CO
5 July 1988	"Supercomputers 2000" by Mr. James Welsh, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
15 July 1988	"Laboratory Observations of Gravity Wave - Critical Layer Interaction" by Dr. Donald Delisi, Northwest Research Associates, Inc., Bellevue, WA
10 August 1988	"Tropical Atlantic Variability" by Dr. P. Delecluse, Universite P. M. Curie, Paris, France

APPENDIX E

Talks, Seminars, and Papers Presented Outside GFDL

During Fiscal Year 1988

17 September 1987	Dr. Kirk Bryan "Response of the Ocean to a CO_2 Climate Change" Florida State University, Tallahassee, FL
17 September 1987	Mr. Anthony J. Rosati "Sea Surface Temperature Prediction" Jet Propulsion Lab. Colloquium on "Large Scale Sea Surface Temperature Variations and Extended-Range Weather Forecasting" Pasadena, CA
18 September 1987	Dr. Syukuro Manabe "Transient Response of a Global Ocean-Atmosphere Model to a Doubling of Atmospheric Carbon Dioxide" Goddard Institute for Space Studies, New York, NY
21 September 1987	Dr. Kikuro Miyakoda "Experiments on Air-Sea Interaction; Systematic Error Workshop; Snow Cover Data" Third Session of the CAS/JAS Workshop Group on Numerical Experimentation, Lisbon, Portugal
25 September 1987	Dr. Jerry D. Mahlman "Requirements for a Class VII Supercomputer at GFDL" OAR FY89 Budget Review, Rockville, MD
5 October 1987	Dr. Abraham H. Oort "The Search for Unity in the Climatic System" and "The Energy Cycle of the Climatic System" Geophysical Institute, Louvain-la-Neuve, Belgium
5 October 1987	Dr. Syukuro Manabe "Two Stable Equilibria of a Coupled Ocean-Atmosphere Model and its Paleoclimatic Implications" Mini-Conference on Possible Causes for the Younger Dryas Event, Lamont Doherty Geological Observatory, New York
13 October 1987	Mr. Michael D. Cox "The State of Deep Circulation P.E. Modelling" World Ocean Circulation Experiment Planning Meeting, Woods Hole, MA
16 October 1987	Mr. Robert E. Tuleya "Numerical Modelling of the Genesis of Tropical Storms" Department of Meteorology, Rutgers University, New Brunswick, NJ
16 October 1987	Dr. J. L. Sarmiento "Ocean Carbon Cycle Dynamics and Atmospheric pCO_2" Lamont-Doherty Geological Observatory, Palisades, NY

19 October 1987	Dr. Charles T. Gordon "Cloud Radiative Forcing and Feedback on One-Month Forecast Experiments with a GFDL GCM" Clouds in Climate II Workshop, Columbia, MD
21 October 1987	Dr. V. Ramaswamy "Line-by-Line Calculations of Solar Water Vapor Absorption" International Radiation Code Intercomparison Group, Columbia, MD
22 October 1987	Dr. John C. Derber "A Global Oceanic Data Assimilation System" Institute of Naval Oceanography, Bay St. Louis, MISS
29 October 1987	Prof. G. L. Mellor "Numerical Simulations of Estuarine Flows" Florida State University, Tallahassee, FL
30 October 1987	Dr. Hiram Levy II "The Global Impact of Combustion Nitrogen Emissions: A Numerical Study" University of Iowa, Chemistry/Chemical Engineering Department, Iowa City, Iowa
2 November 1987	Dr. Jerry D. Mahlman "Status of the Dynamical Hypothesis for Antarctic Ozone Change" Dahlem Workshop on the Changing Atmosphere, West Berlin, West Germany
3 November 1987	Dr. Jack Katzfey "High-Resolution Simulation of the GALE IOP2 Cyclogenesis" GALE-CASP Workshop, Virginia Beach, VA
9 November 1987	Dr. Ngar-Cheung Lau "GCM Modeling of the ENSO Phenomenon at GFDL" Tokyo University, Tokyo, Japan
9 November 1987	Dr. Syukuro Manabe "On the Mid-Continental Dryness Induced by Future Increases of Greenhouse Gases" Senate Committee on Energy and Natural Resources, Washington, DC
9 November 1987	Dr. John C. Derber "An Overview of Data Assimilation Techniques for the Oceans" Global Ocean Flux Study Workshop on Modeling and Data Assimilation, La Jolla, CA
18 November 1987	Dr. Syukuro Manabe "Status of Climate Modeling for the Study of Future Climate Change" NAS/NAE Committee on Magnetic Fusion in Energy Policy, Plasma Physics Laboratory, Princeton, NJ

26 November 1987	Dr. Kikuro Miyakoda (1) "Possibilities and Requirements for Medium and Long-Range Prediction" (2) "ENSO" Workshop on Improving Numerical Weather Prediction in South America, Buenos Aires, Argentina
30 November 1987	Mr. Sydney Levitus "Interpentadal Variability of Temperature and Salinity at Intermediate Depths of the North Atlantic Ocean, 1955-59 versus 1970-74" Atlantic Oceanographic Meteorological Laboratory, Miami, FL
30 November 1987	Mr. R. Najjar "A Three-Dimensional Model of the Marine Carbon Cycle" NASA Goddard Space Flight Center, Greenbelt, MD
3 December 1987	Mr. Sydney Levitus "Interpentadal Variability of Temperature and Salinity at Intermediate Depths of the North Atlantic Ocean, 1955-59 versus 1970-74" Florida State University, Department of Oceanography, Tallahassee, FL
10 December 1987	Dr. Kerry H. Cook "The Laurentide Ice Sheet and North Atlantic Cooling" American Geophysical Union Fall Meeting, San Francisco, CA
11 December 1987	Dr. Samuel George Philander "Recent Results from Coupled Ocean-Atmosphere Models" University of Maryland, College Park, MD
14 December 1987	Dr. Raymond T. Pierrehumbert "Low Order Models" E. Lorenz Retirement Symposium, Massachusetts Institute of Technology, Cambridge, MA
15 December 1987	Dr. John C. Derber "Methodology for Next Generation Analysis and Initialization Systems" Hurricane Analysis Workshop, National Meteorological Center, Camp Springs, MD
15 December 1987	Dr. Yoshio Kurihara "Overview of the GFDL Hurricane Research Program" "Regional Tropical Analysis and Model Initialization: Part II" Hurricane Analysis Workshop, National Meteorological Center, Camp Springs, MD
16 December 1987	Dr. Charles T. Gordon "The Application of NIMBUS 7 ERB Data to Study the Sensitivity of One-Month GCM Forecasts to Specified Cloud-Radiation Forcing" World Climate Research Programme/Joint Scientific Committee Meeting on Radiative Fluxes, Greenbelt, MD

4 January 1988	Mr. Anthony J. Rosati "An Upper Ocean GCM" Institute for Naval Oceanography, New Orleans, LA
5 January 1988	Dr. Kikuro Miyakoda "Atmospheric Forecast Model Data Assimilation and Air-Sea Flux Computations" Workshop on Atmospheric Forcing of Ocean Circulation, Tulane University, New Orleans, LA
18 January 1988	Dr. John R. Toggweiler "Quantitative Models and Conceptual Models as Interpretive Tools in the Global Ocean Flux Study" American Geophysical Union Ocean Science Meeting, New Orleans, LA
18 January 1988	Mr. William J. Hurlin "The Heat Budget of the Tropical Pacific Ocean in a Simulation of the El Nino of 1982-1983" American Geophysical Union/American Society of Limnology and Oceanography, Ocean Sciences Meeting, New Orleans, LA
18 January 1988	Mr. Keith W. Dixon "Freon Uptake and Distribution as Simulated in a World Ocean General Circulation Model" American Geophysical Union/American Society of Limnology and Oceanography, Ocean Sciences Meeting, New Orleans, LA
18 January 1988	Mr. R. Najjar "A Three-Dimensional Model of the Marine Nutrient Cycle" AGU/ASLO Meeting, New Orleans, LA
21 January 1988	Dr. Samuel George Philander "Coupled GC Models of El Nino" Massachusetts Institute of Technology, Cambridge, MA
25 January 1988	Dr. Ngar-Cheung Lau "Variability of Midlatitude Cyclone Tracks in Relation to Low-Frequency Circulation Changes" Department of Atmospheric Sciences, University of Washington, Seattle, WA
26 January 1988	Dr. Samuel George Philander "El Nino and the Southern Oscillation in Coupled GCM's" EPOCS Council Meeting, Seattle, WA
27 January 1988	Dr. Ngar-Cheung Lau "Simulation of ENSO Phenomena by Coupled Models at GFDL" EPOCS Council Meeting, Seattle, WA
29 January 1988	Mr. P. Chang "Oceanic Adjustment in the Presence of Mean Currents" EPOCS Meeting, University of Washington, Seattle, WA

31 January 1988	Mr. Y. Chao "Synoptics of Ocean Heat Content During the 1982/83 ENSO" Conference on Ocean-Atmosphere Interaction, Anaheim, CA
31 January 1988	Dr. Samuel George Philander "El Nino and the Southern Oscillation in Coupled GCM's" American Meteorological Bjerknes Symposium, Anaheim, CA
9 February 1988	Dr. Kirk Bryan "The Oceans' Role in the Climate Response to a CO_2 Warming" Center for Energy and Environmental Studies, von Neumann Building, Princeton University, Princeton,NJ
9 February 1988	Dr. Stephen B. Fels "Effect of Altered CO_2 on the Middle Atmosphere: Radiative and Dynamical Effects" NASA, Greenbelt, MD
16 February 1988	Dr. Kirk Bryan "The Design of Ocean Circulation Models" NATO Workshop "Modelling the Ocean Circulation and Geochemical Tracer Transport" Les Houches, France
19 February 1988	Dr. Isaac M. Held "Modelling the Zonal Asymmetries of Climate" Lamont Doherty Geological Observatory, Palisades, NY
24 February 1988	Dr. Frank B. Lipps "Numerical Simulation of a Squall Line Using a Nested Grid" Eight Conference on Numerical Weather Prediction, Baltimore, MD
25 February 1988	Dr. Jack J. Katzfey "Sensitivity of Numerical Simulations of the President's Day Snowstorm" Eight Conference on Numerical Weather Prediction, Baltimore, MD
25 February 1988	Mr. William F. Stern "The Impact of a Gravity Wave Drag Parameterization on Extended Range Predictions with a GCM" Eight Conference on Numerical Weather Prediction, Baltimore, MD
2 March 1988	Mr. Richard T. Wetherald "Cloud Feedback Processes in a General Circulation Model" Goddard Institute for Space Studies, New York
7 March 1988	Mr. Michael D. Cox "Plans for Future Ocean Modeling at GFDL" World Ocean Circulation Experiment, Numerical Modeling Working Group Meeting, Miami, FL

11 March 1988	Dr. Jerry D. Mahlman "Tracer Structure Around the Northern Polar Vortex" Arctic Ozone Campaign Planning Meeting, NASA Headquarters, Washington, DC
14 March 1988	Dr. Jerry D. Mahlman "Modeling Stratospheric Chemical/Climate Change" Meeting of the Joint Scientific Committee of the World Meteorological Organization, Fort Lauderdale, FL
16 March 1988	Dr. Kirk Bryan "North Atlantic Ocean Circulation and Decadal Climate Changes" World Meteorological Organization/Joint Scientific Committee Meeting, Miami, FL
21 March 1988	Dr. Samuel George Philander 1. "Oceanic Adjustment in the Preserve of Mean Currents" 2. "Results from Coupled General Circulation Models" University of Miami, Miami, FL
23 March 1988	Dr. Jerry D. Mahlman "Theoretical Projections of Stratospheric Change due to Increasing Greenhouse Gases and Changing Ozone Concentrations" Meeting of the National Academy of Sciences, National Research Council Climate Research Committee, Washington, DC
23 March 1988	Dr. Abraham H. Oort "On the Unity in the Climatic System" Department of Physics, University of Lisbon, Lisbon, Portugal
24 March 1988	Dr. Kirk Bryan "Response of the Ocean and Greenhouse Warming" University of Maryland, College Park, MD
28 March 1988	Dr. Hiram Levy II "Impact of Asian and North American Combustion Emission on Mauna Loa" Annual Meeting of GMCC (Global Monitoring for Climatic Change) Hilo, Hawaii
30 March 1988	Dr. Jerry D. Mahlman "General Circulation Models and Trend Detectability" Future of the Stratosphere Meeting, Hilo, Hawaii
7 April 1988	Dr. Syukuru Manabe "Future Change of Climate Induced by Greenhouse Gases" University of Washington, Seattle, WA
8 April 1988	Dr. Syukuru Manabe "Future Change of Climate Induced by Greenhouse Gases" Geophysical Institute, University of Alaska, Alaska

13 April 1988	Dr. Kerry Cook "The Challenge of Global Climate Change" Ramapo State College's Master Lecture Series, Mahwah, New Jersey
19 April 1988	Dr. Stephen B. Fels "The Antarctic Zone Hole - Some Concepts and Background" Annual Meeting of the American Physical Society, Baltimore, MD
25 April 1988	Dr. John R. Toggweiler "Is the Downward DOM Flux Important in Carbon Transport?" Dahlem Conference, Berlin, Federal Republic of Germany
25 April 1988	Dr. V. Ramaswamy "Aerosol Optical Properties and Radiative Effects; Dependence on Single-Scattering Parameters" NOAA/NESDIS Workshop, Camp Springs, MD
27 April 1988	Dr. Samuel George Philander "A WOCE Program for the Tropics" World Ocean Circulation Experiment Meeting, Miami, Florida
29 April 1988	Mr. Robert E. Tuleya "Progress in 3-D Modelling of Tropical Cyclones" Pennsylvania State University, State College, PA
2 May - 30 June, 1988	Mr. Michael D. Cox "Short Course on the GFDL P.E. Ocean Model" Institut fur Meereskunde, Kiel, Federal Republic of Germany
6 May 1988	Dr. Jerry D. Mahlman "High Resolution Modeling of the Stratosphere" University of Chicago, Chicago, IL
9 May 1988	Dr. John R. Toggweiler "Testing an Ocean GCM with Radiocarbon" One Thousand Year Cycle Workshop, Lamont-Doherty Geological Observatory, Palisades, NY
10 May 1988	Dr. Syukuro Manabe "The Role of Atmospheric CO_2 in a Glacial to Inter-Glacial Transition of Climate" 100,000-Year Cycle Conference, Lamont-Doherty Geological Observatory, Palisades, NY
10 May 1988	Dr. V. Ramaswamy "Evolution of Polar Stratospheric Clouds During the Antarctic Winter" Polar Ozone Workshop, Snowmass, CO

16 May 1988	Ms. Bonita Samuels "A Hierarchial Approach to Global Ocean Circulation Modeling" American Geophysical Union Spring Meeting, Baltimore, MD
17 May 1988	Dr. Samuel George Philander "El Nino in Coupled General Circulation Models" American Geophysical Union Meeting, Baltimore, MD
20 May 1988	Mr. Richard T. Wetherald "A Summary of Research Work in the Field of Climate Change due to an Increase of Carbon Dioxide" 25th Reunion of the Meteorological Dept. of the University of Michigan, Ann Arbor, MI
23 May 1988	Dr. Kikuro Miyakoda "ENSO and an Attempt of the Forecast Using an Air-Sea Model" Course on Physical Climatology and Meteorology for Environmental Application" Trieste, Italy
23 May 1988	Dr. Kirk Bryan "Ocean-Atmosphere Coupling" Symposium on "Climate and Geo-Sciences" Louvain-la-Neuve, Belgium
25 May 1988	Dr. Jerry D. Mahlman "The Use of Climate Model Output for Policy Making" Office of Management and Budget Session on Climate Models, Washington, DC
25 May 1988	Dr. Abraham H. Oort "On the Unity in the Climatic System" Department of Physics, University of Lisbon, Lisbon, Portugal
1 June 1988	Dr. R. Murnane "Models of Trace Metal Scavenging" GOFS Workshop on Radiochemistry, Woods Hole, MA
4 June 1988	Dr. Stephen B. Fels "GFDL Results of ICRCCM Exercises" ICRCCM Workshop, College Park, MD
4 June 1988	Dr. V. Ramaswamy "Comparisons Between Exact and Parameterized Calculations of Cloud Heating Rates" Workshop on Radiation Codes, College Park, MD
6 June 1988	Dr. Hiram Levy II "The Regional and Global Distribution of Trace Species Released at the Earth's Surface" Symposium "Long Range Transport of Pesticides" Third International Chemical Congress, Toronto, Canada

9 June	Dr. Samuel George Philander "El Nino in Coupled GCM's" University of Bologna, Bologna, Italy
13 June 1988	Mr. Sydney Levitus "Quality Control of Physical Oceanographic Data" National Oceanographic Data Center, Washington, DC
15 June 1988	Dr. John Derber "A Global Oceanic Data Assimilation System" NMC/CAC Washington, DC
15 June 1988	Mr. Sydney Levitus "Temporal Variability of the Thermohaline Structure of the North Atlantic Ocean at Intermediate Depths" OAR Headquarters, Washington, DC
15 June 1988	Dr. Kikuro Miyakoda "Experimental Prediction Studies on Seasonal Forecasts" NMC/CAC Washington, DC
16 June 1988	Mr. Sydney Levitus "Temporal Variability of the Thermohaline Structure of the North Atlantic Ocean at Intermediate Depths" University of Maryland, College Park, MD
23 June 1988	Dr. Syukuro Manabe "Mid-Continental Summer Dryness Enhanced by Greenhouse Gases" Testify before the Energy and Natural Resources Committee of the U.S. Senate on Issue of the Climate Change Induced by Greenhouse Gases, Washington, DC
27 June 1988	Dr. Isaac M. Held "Stationary Waves: Linear Models vs. GCM's" and "Hadley Cell - Rossby Wave Interactions" National Center for Atmospheric Research, Boulder, CO
28 June 1988	Dr. Jerry D. Mahlman "GFDL Computer Modeling and the NOAA Climate and Global Change Program" OAR Budget Presentation to DOC Budget Office, Rockville, MD
1 July 1988	Dr. J. Pinto ""Neptune: Variations in Aerosol Production Related to the Sunspot Cycle" Conference on Uranus, Pasadena, CA
4 July 1988	Mr. Robert E. Tuleya "A Numerical Investigation of Tropical Storm Genesis Observed During the FGGE Year" Conference on Tropical Meteorology sponsored by the Australian Meteorological and Oceanographic Society, Brisbane, Australia

7 July 1988	Mr. Richard T. Wetherald "Latest Method of GCM Modeling" GCM Intercomparison Workshop, Cambridge, MA
11 July 1988	Dr. Ngar-Cheung Lau "A 30-year GCM Experiment on the Sensitivity of the Atmospheric Circulation to SST Anomalies in the World Ocean" Eleventh Annual Summer Visiting Scientist Seminar Series sponsored by NASA/Goddard Laboratory and University of Maryland, Greenbelt, MD
12 July 1988	Dr. Isaac M. Held "Orographic and Thermally-Forced Stationary Waves: Linear Theory vs. GCM's" National Center for Atmospheric Research, Boulder, CO
14 July 1988	Dr. Abraham H. Oort "An Observational Study of the Atmospheric Energy and Water Budgets in the Arctic and Antarctic" Climate Research Division, ERL, Boulder, CO
25 July 1988	Mr. Thomas L. Delworth "The Influence of Potential Evaporation on the Variabilities of Simulated Soil Wetness and Climate" Workshop on "The Global Water Cycle - Past, Present and Future" Earth System Science Center, Penn State University, State College, PA
26 July 1988	Dr. Isaac M. Held "Hadley Cell-Rossby Wave Interaction and the Maintenance of the Subtropical Jet" National Center for Atmospheric Research, Boulder, CO
28 July 1988	Dr. Kirk Bryan "Bjerknes' Theory of North Atlantic Climate Variability" Global Water Cycle: Past, Present and Future Workshop, Pennsylvania State Earth Science Center, State College, PA
28 July 1988	Mr. Sydney Levitus "Temporal Variability of the Thermocline Structure of the North Atlantic Ocean at Intermediate Depths" Scripps Institute of Oceanography, La Jolla, CA
28 July 1988	Mr. Sydney Levitus "Temporal Variability of the Thermocline Structure of the North Atlantic Ocean at Intermediate Depths" Jet Propulsion Laboratory, Pasadena, CA

8 August 1988	Dr. Hiram Levy II "Global Reactive Nitrogen: A Numerical Simulation of its Distribution" Quadrennial Ozone Symposium, Goettingen, Federal Republic of Germany
8 August 1988	Dr. Frank B. Lipps "On the Role of Snow in a Squall Line Anvil Circulation" Second International Cloud Modelling Workshop, Toulouse, France
8 August 1988	Dr. Jerry D. Mahlman "Climate, Weather, and Chemical Modeling at GFDL" Office of Management and Budget/NOAA, Washington, DC
9 August 1988	Dr. Abraham H. Oort "Atmosphere-Ocean-Solid Earth Interactions in the Cycle of Angular Momentum" Coop Institute for Research in the Atmosphere, Colorado State University, Fort Collins, CO
11 August 1988	Dr. Isaac M. Held "The Madden Julian Oscillation in an Idealized GCM" Center for Atmospheric Theory and Analysis, University of Colorado, Boulder, CO
15 August 1988	Dr. Frank B. Lipps "The Case for Subgrid-Scale Condensation in Numerical Cloud Models" Tenth International Cloud Physics Conference, Bad Homburg, Federal Republic of Germany
18 August 1988	Mr. Marcel D. Schwarzkopf "GFDL Radiation Codes: The Next Generation" International Radiation Symposium, Lille, France
25 August 1988	Dr. John C. Derber "A Variational Nudging Technique for Application to Data Assimilation" NASA/Goddard, Washington, DC
29 August 1988	Dr. Ngar-Cheung Lau "Variability of the Observed Midlatitude Storm Tracks in Relation to Low-Frequency Changes in the Circulation Pattern" Palmen Memorial Symposium on Extratropical Cyclones, Helsinki, Finland
30 August 1988	Dr. Jerry D. Mahlman "Understanding Global Climate Change" Dupont Corporation, Wilmington, DE
7 September 1988	Dr. Samuel George Philander "Interactions Between the Atmosphere and Ocean" Bicentennial Celebration of Harvard's Department of Earth & Planetary Sciences, Boston, MA

9 September 1988 Dr. Jerry D. Mahlman
"Predicting Change in the Physical Climate System"
Briefing of the White House Council of Science Advisors,
The White House, Washington, DC

APPENDIX F

ACRONYMS

ACRONYMS

ALPEX	ALPine EXperiment
ANMRC	Australian Numerical Meteorology Research Centre
A2,E2,E4, F,M	Five physical parameterization packages in use at GFDL, in increasing order of sophistication. E4 physics includes a high-order closure scheme for subgrid turbulence, F physics includes Arakawa-Schubert convective parameterization, and M physics include envelope orography
CAC	Climate Analysis Center (NOAA)
CDC	Control Data Corporation
CLIMAP	Climate: Long Range Investigation, Mapping and Prediction
COADS	Comprehensive Ocean-Atmosphere Data Set
CODE	Coastal Ocean Dynamics Experiment
COLA	Center for Ocean-Land-Atmosphere Interaction
ECMWF	European Centre for Medium-Range Weather Forecast
EEP	Eastern Equatorial Pacific
ENSO	El Nino - Southern Oscillation
FGGE	First GARP Global Experiment- Dec.1978 - Nov.1979 IIIb - Data set analyzed on a spatial grid. 4D- Analysis system taking into account both space and time variation of the data. SOP1 - First Observing Period, Jan.5 - Mar.5,1979 SOP2 - Second Observing Period May 1 - June 30, 1979
GARP	Global Atmospheric Research Program
GATE	GARP Atlantic Tropical Experiment
GCM	General Circulation Model
GFDL	Geophysical Fluid Dynamics Laboratory
HIBU	Federal Hydrological Institute and Belgrade University
ICRCCM	Intercomparison of Radiation Codes in Climate Models
ITCZ	Intertropical Convergence Zone

LAHM	Limited Area HIBU Model
LGM	Last Glacial Maximum
LIMS	Lim Infrared Modulated Sensor
MAC/BES	Meso-alpha coarse model/meso-Beta scale model
MCS	Mesoscale Convective System
Meso α, β, or γ	Three classes of mesoscale atmospheric motion, in descending order of spatial scale.
MIZ	Marginal Ice Zone
MOODS	Master Oceanographic Observations Data Set
MRF	Medium Range Forecast
NESDIS	National Environmental Satellite, Data Information Service
NODC	National Oceanographic Data Center
NOS	National Ocean Service
NMC	National Meteorological Center (USA)
OHC	Ocean Heat Content
PU	Princeton University
ROHK	Royal Observatory of Hong Kong
SAVE	South Atlantic Ventilation Experiment
SESAME	Severe Storms & Mesoscale Experiment
SIB	Simple Biosphere
SKYHI	The GFDL Troposphere-Stratosphere-Mesosphere GCM
SST	Sea Surface Temperature
TOGA	Tropical Ocean Global Atmosphere
TOVS	TIROS-N Operational Vertical Sounder
TTO	Transient Tracers in the Ocean
USGS	United States Geological Survey
WOCE	World Ocean Circulation Experiment

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